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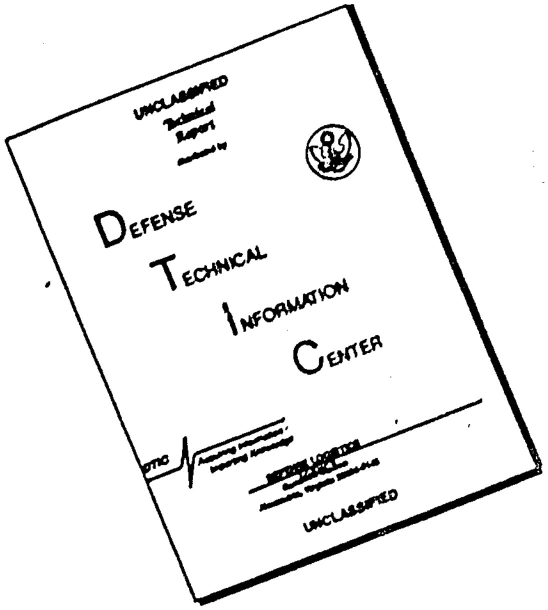

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U S ARMY NATICK LABORATORIES

TECHNICAL REPORT

ES-11

WORLD MAPS OF HIGH DRY-BULB AND WET-BULB TEMPERATURES

EARTH SCIENCES DIVISION

AUGUST 1964

NATICK, MASSACHUSETTS

AD- Div. 7 Accession No.

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Truly high wet-bulb temperatures, close to or above 80°F, are widely spread geographically only under humid tropic conditions of climate. They are found along the Pacific coast of southern Mexico, in the Amazon Basin, the Sudan region of Africa, the Mozambique, Tanganyika and Kenya coasts of Africa, southern and southeastern Asia, the islands of the East Indies, and the north coast of Australia.

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U. S. ARMY NATICK LABORATORIES

Natick, Massachusetts

EARTH SCIENCES DIVISION

Technical Report
ES-11

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Iven V. Bennett, Ph. D.
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Desert and Tropics Laboratory

Project Reference:
1K025001A129

August 1964

FOREWORD

The maps presented in this report are a result of a request from the Army Research Office for information on the worldwide distribution and frequency of high dry-bulb and high wet-bulb temperatures. They are intended primarily for use by the Army Research Office in staff briefing sessions. The report considers temperatures which produce problems for the successful operation of many types of equipment and the proper functioning of personnel engaged in vigorous activity. Special emphasis is placed on wet-bulb temperatures in humid tropics areas, where continuously high values may have harmful physiological effects on men and hasten the deterioration of materiel.

The accompanying textual material is designed to facilitate interpretation of the maps, even by those without a scientific background in climatology. Considerable attention is given to the methods of constructing the maps and to analyses of their accuracy. It is anticipated that these maps will be useful not only to military planners, but to those in many areas of scientific research.

PEVERIL MEIGS, Ph.D.
Chief
Earth Sciences Division

Approved:

DALE H. SIELING, Ph.D.
Scientific Director

CLIFFORD T. RIORDAN
Colonel, QMC
Commanding

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ABSTRACT

This report presents a series of 18 original worldwide maps showing the patterns of extremes but more particularly the frequency and duration of high dry-bulb ($\geq$100°F) and high wet-bulb ($\geq$ 70°F) temperatures. Methods used in drawing the isolines for each map are presented and their accuracy (where estimated) analyzed. Notes are given to assist in interpreting each map or to explain its limitation in specific areas.

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WORLD MAPS OF HIGH DRY-BULB AND WET-BULB TEMPERATURES

INTRODUCTION

1. Purpose

The maps presented in this report were prepared for use by the Army Research Office in staff briefing sessions where extreme accuracy of detail is not required, hence the small scale and the high degree of generalization used in their construction. For this reason they should not be used to obtain data for specific locations. In generalizing at the small scale of the maps (approximately 1:39,000,000), many mesoscale variations had to be ignored. In addition, the scarcity of data for many areas made it necessary to rely frequently on professional judgement in drawing particular isolines.

2. Basic data: source and nature

a. British Air Ministry climatological tables

The basic data for constructing the maps were taken from Tables of Temperature, Relative Humidity and Precipitation for the World, British Air Ministry (1). Because of the short time allotted to complete the maps, it was expedient and convenient to rely on this publication with its excellent worldwide coverage. Record lengths for stations listed in the publication vary from 2 or 3 to over 70 years, but no attempt was made in preparing the maps to reduce any of the data used to a common period. As described below, other sources of data were used in preparing the report, but in all cases values plotted on the maps were taken directly from or calculated from data given in the British Air Ministry publication.

b. United States Weather Bureau data

The United States Weather Bureau publication, Local Climatological Data (2), was used as a source for daily and hourly data to develop certain methods used in constructing the maps. (See part I, sections 4 and 6.)

c. Yuma, Arizona, and Panama Canal Zone climatic analog data

Data taken from Analogs of Yuma Climate, I-XI (3) and Analogs of Canal Zone Climate, I-X (4) were used to guide the drawing of isolines on certain of the maps. (See Part I, section 4.)

PART I. CONSTRUCTION AND INTERPRETATION OF THE MAPS

A. Dry-bulb Temperature Maps

1. "Warmest month"

For the dry-bulb temperature maps, all station data are for the warmest month at each station. This month, of course, varies from station to station, so any one map may be based on data from several different calendar months. The "warmest month" is defined as the single month with the highest mean daily maximum for the entire period of record. Where more than one month registered the highest mean daily maximum, the month with the highest mean monthly maximum temperature was selected, and if the mean monthly maximum was the same for 2 or more months, the choice consisted of the month containing the absolute maximum.

Defined in this way, the "warmest month" will produce temperature statistics slightly lower than where the warmest month for each year is used to compute statistics for the period of record without regard to the month in which it happens to occur during any one year. This is shown in Table I. At Dallas, for example, during the period 1949-1961 the mean daily maximum temperature, when based on the warmest month each year (during the 13 years, July was the warmest month 7 times, August 5 times, and June once) is 97.4°, compared to 95.8° for the mean warmest single month (July) over the entire 13 years.* If the warmest 30-day period each year (with no regard given to coincidence with calendar months) were used as a base for compiling "warmest month" statistics for a period of record, this definition of "month" would produce an even higher mean daily maximum temperature. It is apparent, therefore, that the data shown on the maps will underestimate the warmest month-long conditions that men and materiel could be expected to meet in a given area over a period of years.

2. Plate I. Warmest month - mean daily maximum temperature

Mean daily maximum temperature, as defined here, is the arithmetic mean of all daily maxima for the particular month selected as the warmest of the period of record.

It is often wrongly assumed that 50 percent of the days at a given station will have higher (or lower) temperatures than the mean daily maximum. This is generally not true for warm climates. An investigation of the frequency distribution of daily maxima for 6 stations (five in the southwestern United States and San Juan, Puerto Rico) produced the data

*All temperatures in this report are given in degrees Fahrenheit.

shown in Table II. For the 6 stations, the percent of days with maximum temperatures equaling or exceeding the mean daily maximum varies from approximately 56° to 62°, hence the mean daily maximum apparently cannot serve as an exact indication of the 50th percentile.

This departure of the mean from the median is caused by occasional days in the record of each station with unusually low maximum temperatures. In other words, the low temperature end of the frequency distribution lies farther from the mean than does the high temperature end. At Las Vegas, Nevada, for instance, the lowest daily maximum for the 11-year period of record of Table II was 81°, or 23 degrees below the mean, while the highest was 116°, only 12 degrees above the mean (see also Fig. 1). This general relationship is almost universally true during the warm season in areas with hot climates, consequently, nearly without exception the mean daily maxima of Plate I will be exceeded on more than 50 percent of the days.

3. Plate II. Warmest month - mean monthly maximum temperature

The mean monthly maximum temperature is the arithmetic mean of the year-by-year maxima for the month in question. If June is the warmest month for a particular station, the absolute June maxima for each year of the record are totaled, the mean obtained, and the result termed the "mean monthly maximum" for June for that period.

The data in Table II indicate that 5 to 10 percent of the days of the warmest month may have maxima which equal or exceed the mean monthly maximum temperature of that month. On a percentage-of-time basis, it has been found that hourly temperatures above the mean monthly maximum occur about 1 percent of the time in an average summer month.* Table I shows that the warmest-month mean monthly maxima as determined in this report will be 1 or 2 degrees lower than the mean monthly maxima based on the warmest month of each year.

4. Plates III - VII. Warmest month - frequency of days with maximum temperature ≥100°, ≥105°, ≥110°, ≥115°, and ≥120°

The frequency data for this series of maps were estimated from a nomograph (Fig. 2), the original version of which appeared in QM R&E Command Special Report 61, Frequency and Duration of High Temperatures (5). In constructing the original nomograph, actual daily maximum temperatures of the warmest month for 31 stations in the United States (19 to 20 years of record) and 25 foreign stations (1 to 4 years of record) were used to compute percentage frequencies of occurrence for ≥110°, ≥115°, and ≥120°. These station frequencies were used to construct the 110°, 115° and 120°

*Based on unpublished work of the Earth Sciences Division.

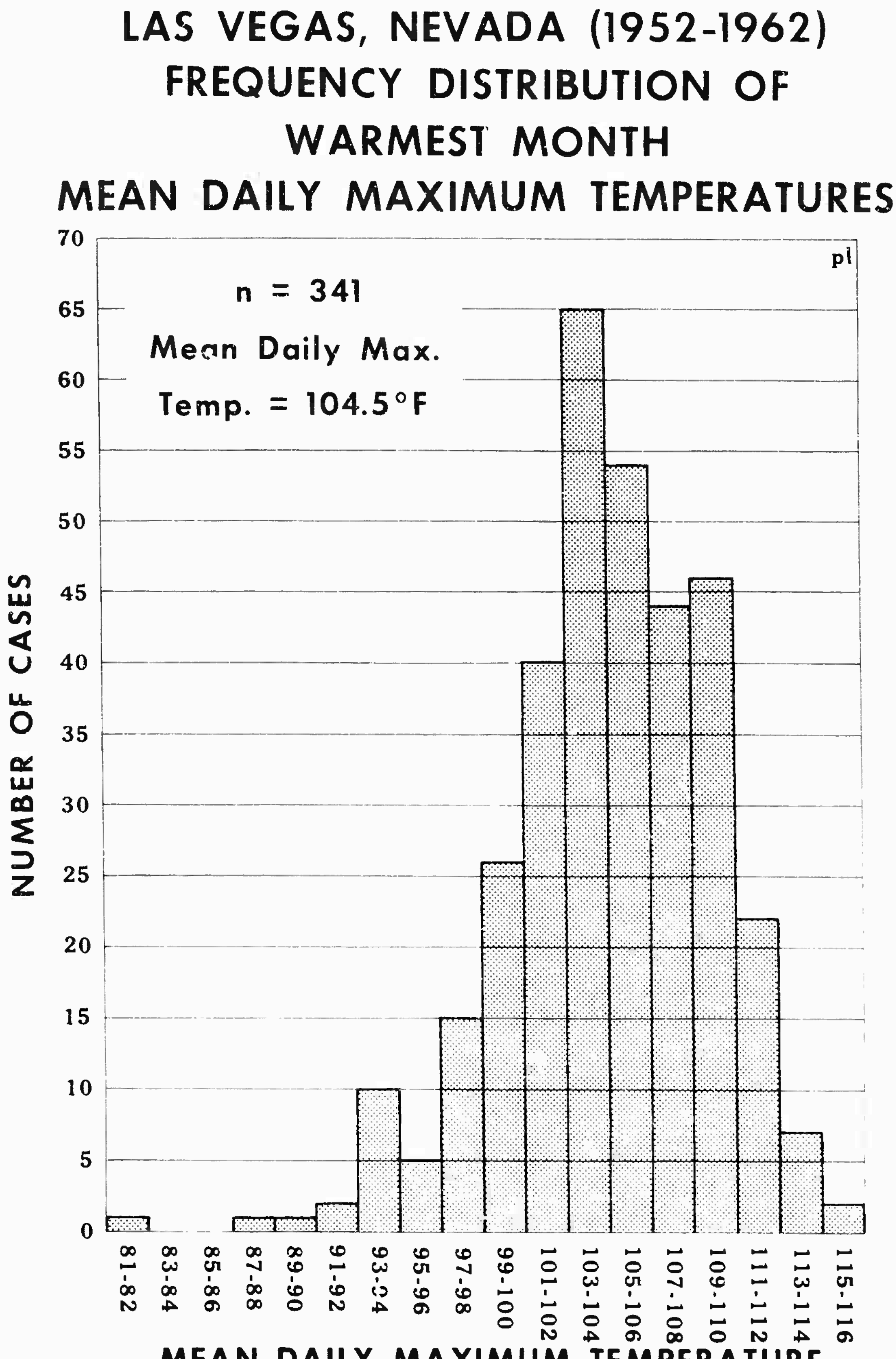
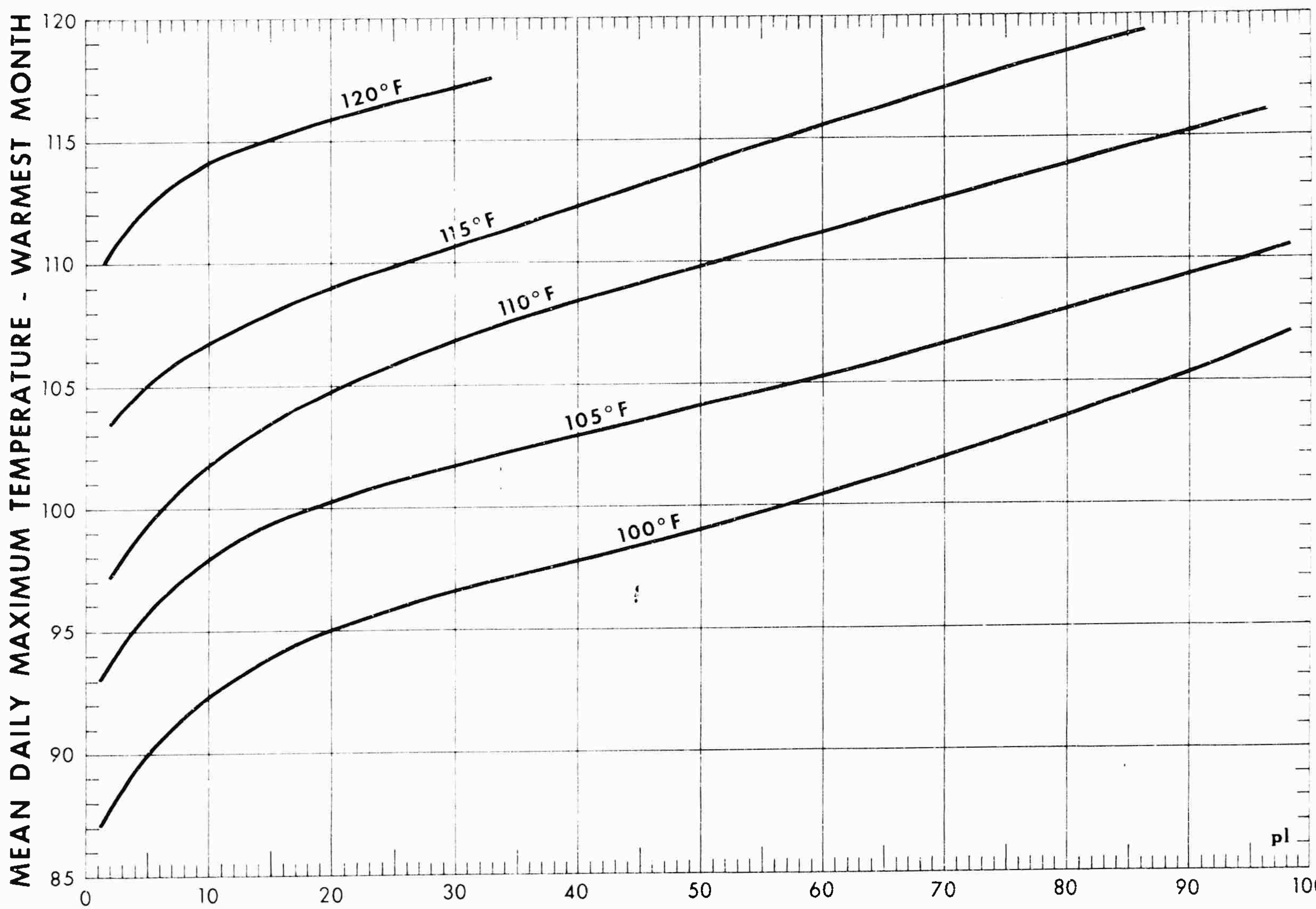

LAS VEGAS, NEVADA (1952-1962)
FREQUENCY DISTRIBUTION OF
WARMEST MONTH
MEAN DAILY MAXIMUM TEMPERATURES
n = 341
Mean Daily Max.
Temp. = 104.5°F
NUMBER OF CASES
MEAN DAILY MAXIMUM TEMPERATURE
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
81-82
83-84
85-86
87-88
89-90
91-92
93-94
95-96
97-98
99-100
101-102
103-104
105-106
107-108
109-110
111-112
113-114
115-116

Figure 1

NOMOGRAPH FOR ESTIMATING PERCENTAGE FREQUENCIES OF MEAN DAILY MAXIMUM TEMPERATURES



PERCENTAGE FREQUENCY OF OCCURRENCE OF DAILY MAXIMUM TEMPERATURE AT OR ABOVE INDICATED LEVEL

Figure 2

TABLE I. COMPARISON OF MEAN MAXIMUM TEMPERATURE (DAILY AND MONTHLY) COMPUTED FROM: a) WARMEST MONTH EACH YEAR AND b) WARMEST MONTH OF PERIOD OF RECORD

Station	Period of Record	Mean Daily Max Temp Based on "Warmest month": Each year	Mean Daily Max Temp Based on "Warmest month": Entire period	Mean Monthly Max Temp Based on "Warmest month": Each Year	Mean Monthly Max Temp Based on "Warmest month": Entire period
Dallas, Tex.	'49-'61	97.4	95.8 (Jul)	105.6	103.4 (Jul)
El Paso, Tex.	'50-'60	96.7	96.1 (Jun)	104.9	104.1 (Jun)
Tucson, Ariz.	'50-'62	99.7	99.1 (Jun)	108.4	107.7 (Jun)
Yuma, Ariz.	'49-'62	108.5	107.9 (Jul)	117.4	115.3 (Jul)
Des Moines, Ia.	'49-'62	86.8	86.0 (Jul)	98.4	96.6 (Jul)
San Juan, P.R.	'49-'61	86.2	86.0 (Sep)	92.9	91.5 (Sep)

TABLE II. PER CENT OF DAYS WITH MAXIMUM TEMPERATURES AT OR ABOVE MEAN DAILY MAXIMUM AND MEAN MONTHLY MAXIMUM TEMPERATURES

Station	% of Record	No. Days*	Mean Daily Max. Temp.	% of Days at or above Mean Daily Max.	Mean Monthly Max. Temp.	% of Days at or above Mean Monthly Max.
Yuma, Ariz.	'49-'62	434	108.5	56.1	115.8	4.6
Fresno, Calif.	'49-'62	434	98.5	61.3	106.2	6.9
Las Vegas, Nev.	'52-'62	341	104.5**	56.6	111.9	6.2
Dallas, Tex.	'49-'61	402	97.4	57.5	105.0	7.0
Little Rock, Ark.	'49-'62	433	93.4	53.6	100.6	12.2
San Juan, P.R.	'50-'61	367	88.0	61.6	91.8	7.1

*i.e., total number of days in the warmest month, during the period of record indicated.

**The lowest daily maximum temperature for the period was 81° (23 degrees below the mean); the highest daily maximum temperature for the period was 116° (only 12 degrees above the mean). These data, for Las Vegas, are plotted on Figure 1.

lines shown in Figure 2 of this report. For the present series of maps, the 100° and 105° lines were added by plotting frequencies of those values for 18 stations in the United States with 20 years of record. Eighteen stations were considered a sufficient number to plot since the data for these stations produced lines of best fit that corresponded closely to the trend of the higher-value temperature lines of the original nomograph.

Frequency data used to construct Plates III through VII were obtained by using the "warmest month" mean daily maximum temperature from the British Air Ministry publication as the dependent variable to enter the nomograph. In this manner, frequency data were obtained for nearly 400 stations scattered around the world.

As stated in Special Report 61 (5), "The frequencies have a reasonably satisfactory validity above values of about 2 percent, except in the monsoon area of India and some tropical areas, where the abrupt start of the rainy season sharply terminates the preceding dry, hot season at varying times after the beginning of the month, thus distorting the relationship between means and frequencies."

In plotting frequencies for the $\geq 100°$ map a difficulty was encountered. Several humid-tropic stations, particularly those with maritime locations, had warmest-month mean daily maximum temperatures near 90°, which, when used to enter the nomograph, indicated approximately 5 percent of the days could be expected to have maximum temperatures $\geq 100°$. A check of absolute maxima indicated, however, that some of the stations had never experienced temperatures at or above 100°. This error is due to the fact that the method was developed from stations located almost entirely in mid-latitude, continental climates where the range of daily maxima about the mean is considerably greater than in humid-tropic areas.* The error was avoided, at least to some extent, by using the period-of-record absolute maximum temperature as a control over frequencies in the preparation of all maps in the series. If the absolute maximum indicated that temperatures had never actually exceeded the particular level, a zero frequency was plotted for that station regardless of the value taken from the nomograph.**

---

*For example, Iloilo, in the Philippine Islands (10°42' N) and Grand Junction, Colorado (39°07' N):

	Iloilo	G. Junction
Warmest month mean daily maximum temp	92	92
Absolute maximum	98	105
Absolute minimum	67	-21

**Since absolute maxima are available for a greater number of stations than are the monthly mean daily maxima, the absolute maxima were used to assist drawing isolines in areas lacking data to compute frequencies. In doing this, the two series of publications, Analogs of Yuma Climate (3) and Analogs of Canal Zone Climatic (4), were of great value in providing data for many stations not included in the British Air Ministry publication.

5. Plates VIII - XI. Warmest month - frequency of hourly temperatures $\geq 100°$, $\geq 105°$, $\geq 110°$, and $\geq 115°$

The frequencies given in this group of maps are for the percent of total hours of the entire month (selected as the warmest) at or above the designated temperature levels. In other words, of the 720 hours of a 30-day month (including nighttime hours) a certain percentage can be expected to occur at or above the indicated temperatures.

Frequencies were calculated by machine from data punched on EAM cards using a method developed by Dr. Earl E. Lackey of the Earth Sciences Division (6). The three climatic statistics required for application of the method are: 1) the period-of-record mean, 2) absolute maximum temperature, and 3) absolute minimum temperature for the month being considered. The success of the method, which was developed from data of 20 stations located between 12° and 70° N. Lat., depends on the similarity - among different climates - of the normalized cumulative frequency curves of hourly temperatures for given positions of the mean monthly temperature between the absolute extremes. The frequency of any temperature is thus expressed as an empirical function of that temperature on a normalized 100-point scale, the functional parameters being the locations of extremes and the asymmetrical position of the mean.

Performance of the Lackey method was tested against actual hourly temperature frequencies of 40 widely scattered stations, including several located within the tropics. A large number of estimated percentile frequency levels were checked against known levels, and it was found that 90 percent were within ±5 degrees of the actual temperature level of the percentile. (As an example: if the estimated 5 percent frequency for a given station is 100°, the chances are approximately 90 out of 100 that the true level for that frequency is ±3 degrees either side of 100°.) The greatest errors discovered in the method were in continental middle and high latitudes where temperature ranges were greatest, and the smallest errors were in the humid tropics.

6. Plates XII & XIII. Warmest month, mean duration (hours) of hot spells with temperatures $\geq 100°$ and $\geq 105°$

Hot spells are defined for this study as periods of 1 hour or more with temperatures continuously at or above specified levels.

The mean duration for the warmest month was determined by dividing the total number of hours of such spells by the number of days on which they occurred. If a 10-year period at a station has 40 days with hot spells $\geq 100°$ that total 400 hours, the mean duration is 4.0 hours. Such a statistic is made more valuable, of course, if supported with data giving the frequency of days with temperatures $\geq 100°$. If a station were to have only one hot spell $\geq 100°$, with that hot spell lasting several hours, the lack of information that this occurred only once would give a false impression concerning hot spells at that station. Consequently, these two "duration" maps should be consulted together with the two maps showing the frequency of days $\geq 100°$ and $\geq 105°$ (Plates III and IV).

The hourly data necessary to determine hot spell durations are readily available for only a few places in the world, and the task of computing durations from actual data for large numbers of stations would have required considerably more time than was allotted for the completion of these maps. Therefore, an attempt was made to develop a method by which estimates could quickly be made from the data available in the British Air Ministry publication. The method finally adopted for use is based on the assumption that the higher the mean daily maximum temperature for a particular month, the longer, on the average, the temperature will remain above specified levels.

To test this hypothesis, 10 years of warmest-month hourly data for 38 stations in the United States were used to establish the mean duration in hours of hot spells with temperatures $\geq 100°$ and $\geq 105°$. Regression and correlation analysis were then used to establish the nature of the relationship between these duration statistics and warmest-month mean daily maximum temperatures. It was found that both the $\geq 100°$ and $\geq 105°$ data were significantly correlated with mean daily maximum temperature and that the relationship was best expressed in the linear form, $Y' = a + bX$ (see Figs. 3 and 4). Correlation statistics for the 100° hot spell relationship were: $r_{xy} = 0.96$, $r^2_{xy} = 0.91$ and $S_{yx} = 0.55$; for the 105° relationship: $r_{xy} = 0.79$, $r^2_{xy} = 0.62$, and $S_{yx} = 1.06$. The coefficients of determination (r^2_{xy}) indicate that changes in mean daily maximum temperature account for 91 percent of the variance from the mean of durations of $\geq 100°$ hot spells, and for 62 percent of the variance from the mean of durations of $\geq 105°$ hot spells. The standard errors (S_{yx}) show that the departure from the regression line (Figs. 3 and 4) for two thirds of the $\geq 100°$ estimated durations are ≤ 0.55 hours, and ≤ 1.06 hours for the $\geq 105°$ estimated durations; and that 95 percent of the $\geq 100°$ estimated durations will be in error by 1.1 hour or less, and 95 percent of the estimated $\geq 105°$ durations will be in error by 2.1 hours or less.

From these statistics it can be seen that the method is capable of estimating hot-spell durations within reasonable error limits. Therefore, the regression equations were used to calculate such durations for approximately 400 stations. The resulting data were used to construct the $\geq 100°$ and $\geq 105°$ maps. (Sufficient hot-spell data were not available to establish valid relationships for the 100°, 115°, and 120° levels.)

WARMEST MONTH
RELATIONSHIP BETWEEN HOURLY DURATION OF TEMPERATURES ≥ 100°F AND MEAN DAILY MAXIMUM TEMPERATURE.

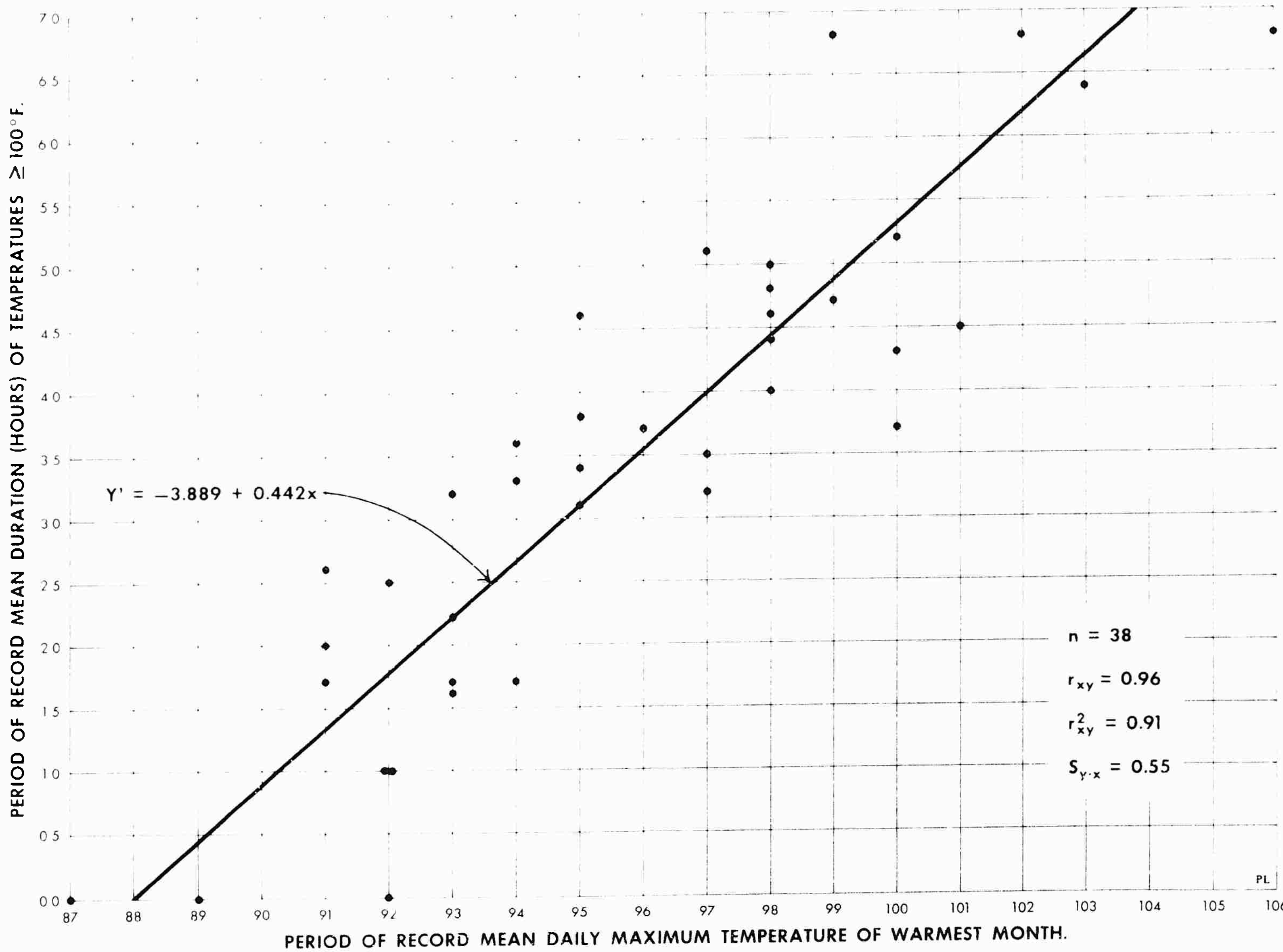


Figure 3

WARMEST MONTH
RELATIONSHIP BETWEEN HOURLY DURATION OF TEMPERATURES ≥ 105°F AND MEAN DAILY MAXIMUM TEMPERATURE.

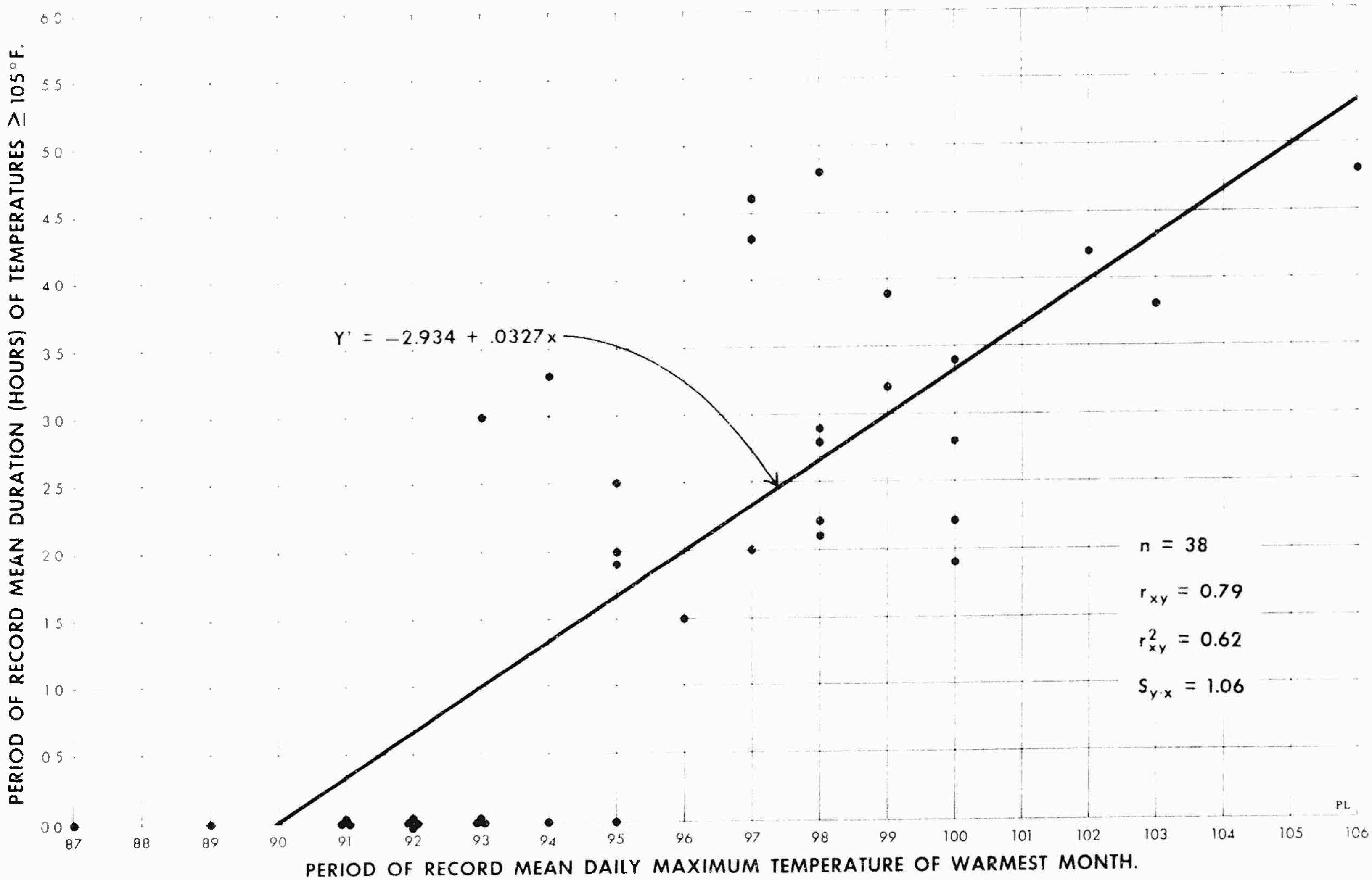


Figure 4

7. <u>Plate XIV - Number of months per year with mean daily maximum temperatures $\geq 100°$</u>

The data for this map were obtained by counting, in the British Air Ministry publication, the number of months of the year with mean daily maximum temperatures $\geq 100°$.

8. <u>Plate XV - Number of months per year with mean monthly maximum temperatures $\geq 100°$</u>

Similarly, the data for this map were obtained by counting in the British Air Ministry publication, the number of months of the year with mean monthly maximum temperatures $\geq 100°$.

B. Wet-bulb Temperature Maps

1. "Most humid month"

For the wet-bulb temperature maps, all station data are for the most humid month at each station. As in the case of the dry-bulb temperature maps, this month varies from station to station, so any one map may be based on data from several different calendar months. The "most humid month" is defined as the month with the highest mean daily maximum wet-bulb temperature, provided certain precipitation requirements discussed below are fulfilled.

2. Computation of wet-bulb temperature - introduction

Reliable wet-bulb temperature data are not available for many parts of the world, particularly for the humid tropics where continuously high values may have harmful physiological effects on men and hasten the deterioration of materiel.* It was necessary, therefore, in the preparation of these maps to develop methods for estimating wet-bulb temperature from a type of data commonly available for a large number of stations.

It was decided that any methods (relying, as these must, on temperature as the key variable for making estimates) would be dependable only at times with sufficient precipitation to insure the presence of abundant green vegetation or continuously damp ground. Such conditions come close to insuring the presence of air with moisture content high enough to produce saturation nearly every night. This condition must be approximated for one of the methods (discussed later) to be valid. This rainfall requirement also has the advantage of eliminating from consideration arid lands where during certain seasons the influx of air with relatively high water vapor content produces wet-bulb temperatures high enough to include them in the group ($\geq 70°$) established for these maps. Though these dry lands (southwestern Arizona is an example) at times experience high wet-bulb temperatures, the associated low relative humidity and lack of rainfall prevent development of the host of problems caused in the humid tropics by the prevalence of warm air continuously near saturation.

Mean monthly rainfall was used as the variable to determine whether a station met the humid tropic requirement. Considerable subjective judgement was used in establishing the amount of rainfall necessary to qualify a particular month at a given station. For instance, if the month under consideration occurred near the beginning of the rainy season, 4 inches met

*The Army Research Office, for whom these maps were prepared, requested that they be limited to areas where so-called "humid-tropical" conditions occur at least one month of the year.

the requirement for humid tropic classification. If the month concerned fell at the end of the rainy season, 1 inch was considered sufficient. If there were no dry season, 1.5 to 2 inches per month was considered enough to classify as humid tropic.

3. Plate XVI. Most humid month, mean daily maximum wet-bulb temperature

Two methods were used to compute monthly mean daily maximum wet-bulb temperatures for this map. The first, called the "assumed dew point" method, was based on the assumption that the monthly mean daily minimum dry-bulb temperature is close to the monthly mean dew point, and that the dew point does not change radically during the day. (This last is usually true in areas where humidities and rainfall are fairly high.) In this method, average maximum wet-bulb temperatures were computed using the monthly mean daily minimum temperature as though it were the dew-point temperature at the time of average maximum temperature. If the daily minimum temperature does not always fall to the dew point, as occurs frequently in dry climates and occasionally in humid tropic climates, this method will overestimate the average wet-bulb temperature.

In the second method, called the "relative humidity" method, the monthly mean daily maximum wet-bulb temperature was computed from the mean daily maximum dry-bulb temperature and the afternoon relative humidity. If the time of maximum dry-bulb temperature coincides with the time for which the afternoon relative humidity is given, average maximum wet-bulb temperatures can be computed with reasonable accuracy. Unfortunately, these two times do not usually coincide and any variation results in a computed average maximum wet-bulb temperature higher than that actually occurring.

Each of these methods was applied to the data of the approximately 400 stations available in the British Air Ministry publication. The lower of the estimates produced by the two methods was plotted on the map, since in either method errors are likely to consist of overestimating the wet-bulb temperature.

The above methods were tested against a number of stations whose actual mean monthly daily maximum wet-bulb temperatures were known. Maximum errors in areas of humid tropic climate (meeting the rainfall requirement) were not greater than 1 degree, but as dry climatic conditions were approached, errors increased rapidly. At Yuma, Arizona, the error was 15 degrees using the "assumed dew point" method, and 5 degrees using the "relative humidity" method. Using the lower value of these two methods, as was done in plotting the map, the following errors were observed:

Wet Tropic Areas	Error (°F)
Fort Benning, Georgia	+ 0.1
Cape Canaveral, Florida*	+ 0.2
Anderson Air Force Base, Guam	+ 0.4
Transition Areas	
Honolulu, Hawaii	+ 1.1
Midway Island	+ 2.8
Austin, Texas	+ 3.0
Dry Areas	
El Paso, Texas	+ 4.0
Yuma, Arizona	+ 5.1
Dhahran, Saudi Arabia	+18.0

4. Plate XVII. Most humid month, mean daily minimum wet-bulb temperature

This map was constructed with data for the same stations and months used for the mean daily maximum wet-bulb temperature map (Plate XVI). The values plotted on the map were estimated directly from the mean daily minimum dry-bulb temperature under the assumption implicit in the "assumed dew point" method described for Plate XVI that the dew point and mean daily minimum temperature will be very close together. Since the wet-bulb temperature always lies between the dry-bulb temperature and dew-point temperature, except at saturation (when wet bulb and dew point are identical), errors expected from estimating the mean daily minimum wet-bulb temperature directly from the mean daily minimum dry-bulb temperature will be smaller than those reported for Plate XVI.

5. Plate XVIII. Number of months per year with mean daily maximum wet-bulb temperatures $\geq 70°$

Estimation of wet-bulb temperatures for this map was done with the methods described for Plate XVI. After a value for the mean daily maximum wet-bulb temperature was established for each month of the year at a given station, the number of months in which the value was equal to or greater than 70° were counted to prepare data for the maps.

*Now Cape Kennedy, Florida

PART II. DISCUSSION OF DISTRIBUTION OF HIGH TEMPERATURES

1. Distribution of high dry-bulb temperature

The outstanding feature of the distribution of high dry-bulb temperature is the large concentration in Saharan Africa and southwestern Asia of a large proportion of the total world area with high dry-bulb temperatures. Within this stretch of arid land, larger in area than the United States, only immediate coastal districts and scattered mountains and high plateaus are outside the $\geq 100°$ category. Included in the $\geq 100°$ category are virtually all of Saharan Africa and large parts of the Arabian peninsula, Iraq, West Pakistan and India. Nearly all of the Sahara and large areas in Saudi Arabia, Iraq, West Pakistan and India commonly experience temperatures between 105° and 110°, while a large part of the western Sahara has temperatures that exceed 110° and even 115°. In contrast, as soon as the temperature rises much above 100°, or the frequency of days or hours with temperature $\geq 100°$ gets large, areas in these categories mapped in other parts of the world diminish considerably in size or disappear altogether.

Plate I, Warmest Month - Mean Daily Maximum Temperature, may be taken as an example of this concentration of high temperatures in northern Africa and southwestern Asia. The map (which shows areas with approximately 50 to 60 percent of the days with temperatures equal to or greater than the levels specified) indicates that even in the warmest month, temperatures $\geq 100°$ are not common outside of the Sahara-southwest Asia area.

In North America, warmest-month mean daily maxima $\geq 100°$ are limited to parts of the southwestern United States and small, scattered areas in Mexico. The southern one-third of the Central Valley of California, which has a reputation for summer heat, just reaches this level (Fresno, 100°; Bakersfield, 101°), as does the lower Rio Grande Valley (Laredo, 100°). Highest temperatures in North America occur on the floors of low basins of the Basin and Range Province in southeastern California, southern Nevada, and southwestern Arizona and adjacent parts of Mexico: e.g., Greenland Ranch, on the floor of Death Valley, reaches 116°; Yuma, 106°; Phoenix, 104°; Las Vegas, 103° (on the other hand Tucson, at an elevation of only 2,600 feet has recorded only 99°). A thin strip in northwestern Mexico between the coast and the Sierra Madre Occidental, a portion of the Rio Balsas Valley, and central Yucatan complete the picture of incidence of 100° temperature in North America.

In the southern Hemisphere, only northern Australia has substantial areas in which half or more of the days in the warmest month reach or exceed 100°. Some of the maps, e.g., Plate II, Warmest Month - Mean Monthly

Maximum Temperature, indicate that all of Australia expects these high temperatures (except Tasmania and the eastern highlands and coast). Considering the low latitude and aridity, both of which contribute to high incoming amounts of radiant energy, this is not surprising. However, temperatures seldom exceed 115°, which is common to parts of the Sahara. In Southern Africa, temperatures above 100° are experienced principally in Bechuanaland and the lowlands of Mozambique and Southern Rhodesia. South America has a large hot area that extends from the northern Pampas to the Gran Chaco of Paraguay and Bolivia and across the Mato Grosso to arid northeastern Brazil. Temperatures of most of northeastern Brazil, however, seldom exceed 105° due to the moderate elevation of the plateau surface.

2. Distribution of high wet-bulb temperature

For reasons explained earlier in this report, wet-bulb temperature was mapped only for areas with humid tropic conditions at least one month per year. Consequently there is bias in the distribution of high wet-bulb temperatures shown by the maps. The areas presented in the three wet-bulb temperature maps comprise, however, most of the major ones in which wet bulb temperatures $\geq$70° are experienced with any reasonable frequency.

There are a few arid sections of the world (e.g., the southwestern United States) where air mass moisture content produces wet-bulb temperatures $\geq$70° at certain times of the year. However, such arid regions will not experience wet-bulb temperatures much in excess of this value except in the midst of heavily irrigated and cultivated tracts of land. During a 5-year period at Yuma and Phoenix, Arizona, mean wet-bulb temperatures for 12:00 to 14:00 hours LST (close to the time of maximum wet bulb temperatures on most days) were 73° for July and August (the most humid months for both stations.) Wet-bulb temperatures commonly soar considerably above 70°, and sometimes above 80°, around the Red Sea and the Persian Gulf. With the above exception, truly high wet-bulb temperatures close to or above 80° are found extensively only under humid tropic conditions.

Such humid tropic conditions with wet-bulb temperatures $\geq$80° occur along the Pacific coast of southern Mexico, in the Amazon Basin, the Sudan region of Africa, the Mozambique, Tanganyika and Kenya coasts of Africa, southern and southeastern Asia, the islands of the East Indies, and the north coast of Australia. In northeastern India during the wet monsoon and in a few other small areas, values over 85° are experienced. Such values also occur in such lower middle latitude humid areas as the Gulf coast of the United States and the lower Yangtze Valley of China.

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5. Meigs, Peveril. Frequency and Duration of High Temperatures, Special Report 61, Environmental Protection Research Division, Hq. Quartermaster Research & Engineering Command, U.S. Army, Natick, Mass., August 1953

6. Lackey, Earl E., "A method for assessing hourly temperature probabilities from limited weather records" Bulletin of the American Meteorological Society, 31(6):298-303, June 1960.

Acknowledgments

Several individuals contributed to this work. Mr. Howard Ohman, Mr. John James, Mr. Jack Chambers, and Lt. Gordon Nishimoto assisted in the preparation of the maps. Cartography was performed by Miss Pernel Leuvelink, under the supervision of Mr. Aubrey Greenwald.

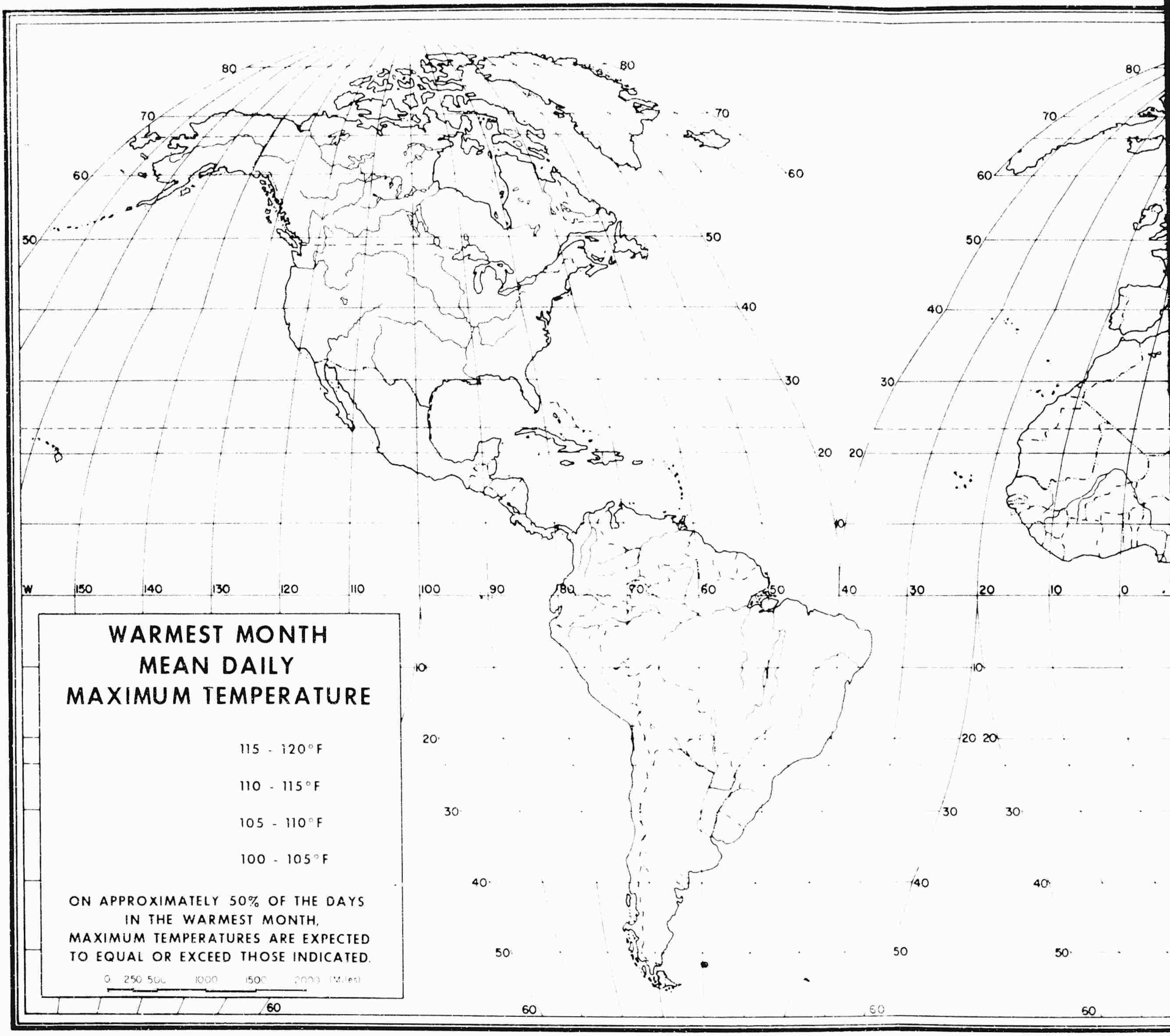
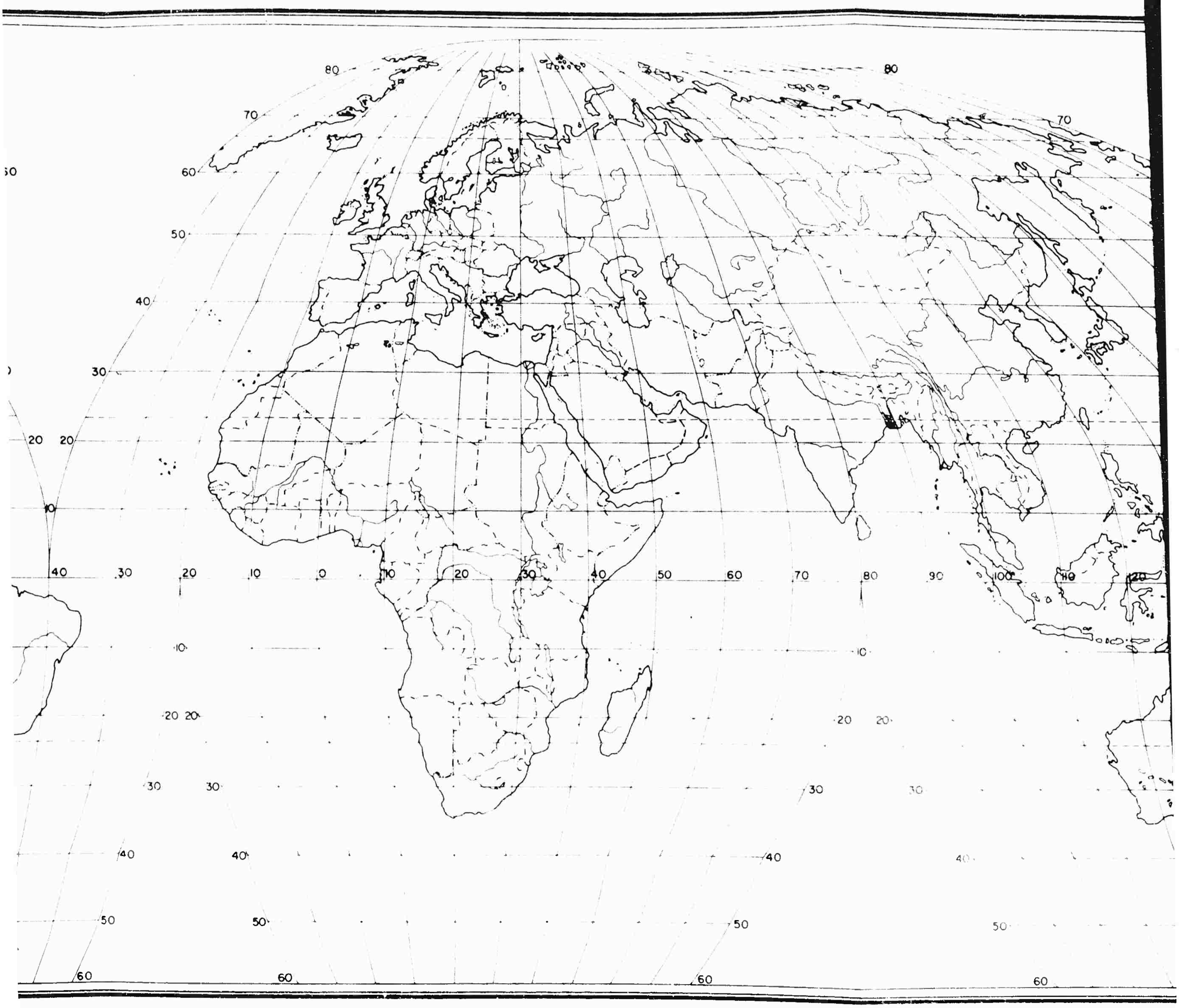

WARMEST MONTH
MEAN DAILY
MAXIMUM TEMPERATURE
115 - 120°F
110 - 115°F
105 - 110°F
100 - 105°F
ON APPROXIMATELY 50% OF THE DAYS
IN THE WARMEST MONTH,
MAXIMUM TEMPERATURES ARE EXPECTED
TO EQUAL OR EXCEED THOSE INDICATED.
0 250 500 1000 1500 2000 (Miles)

Plate I



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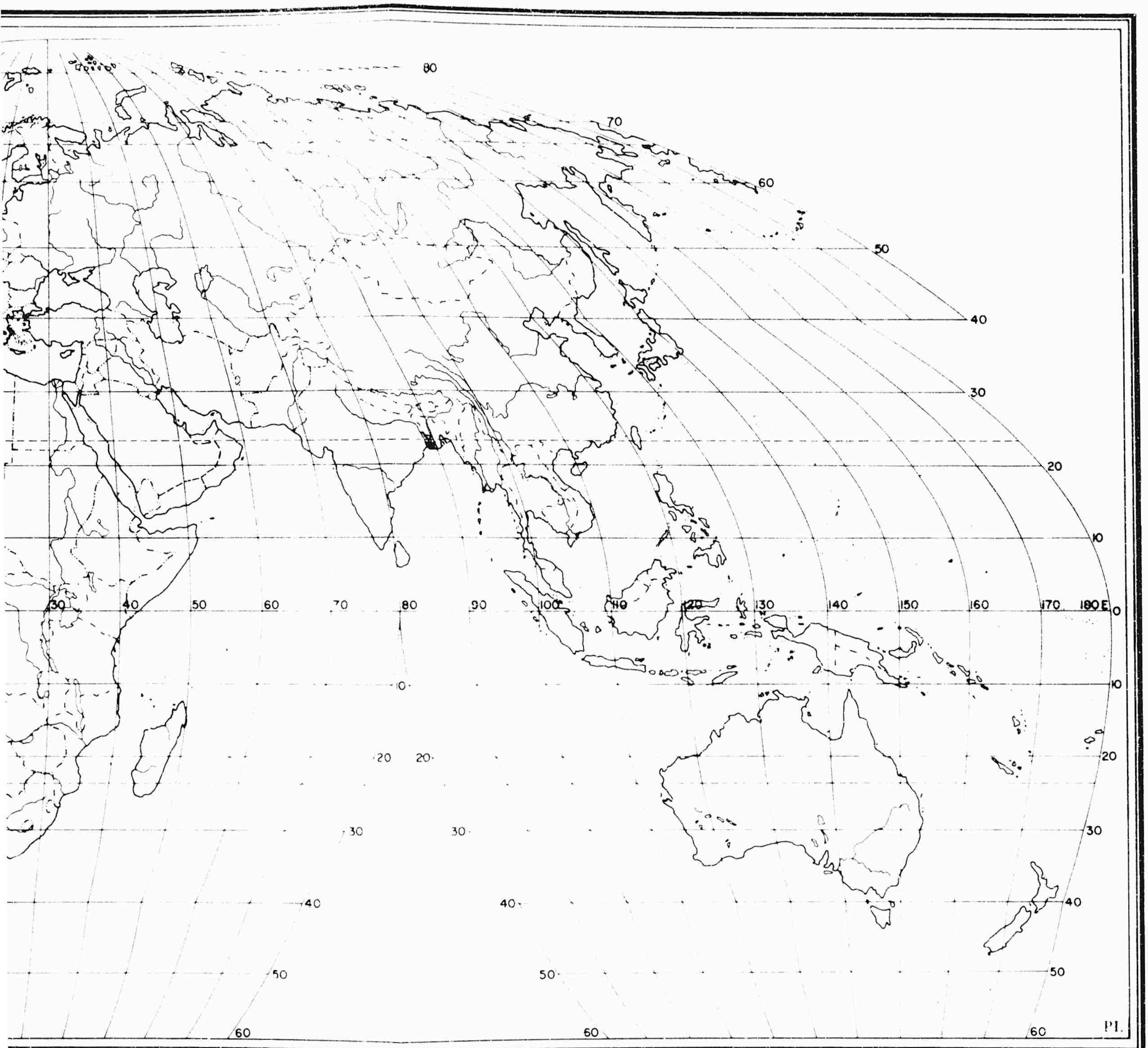

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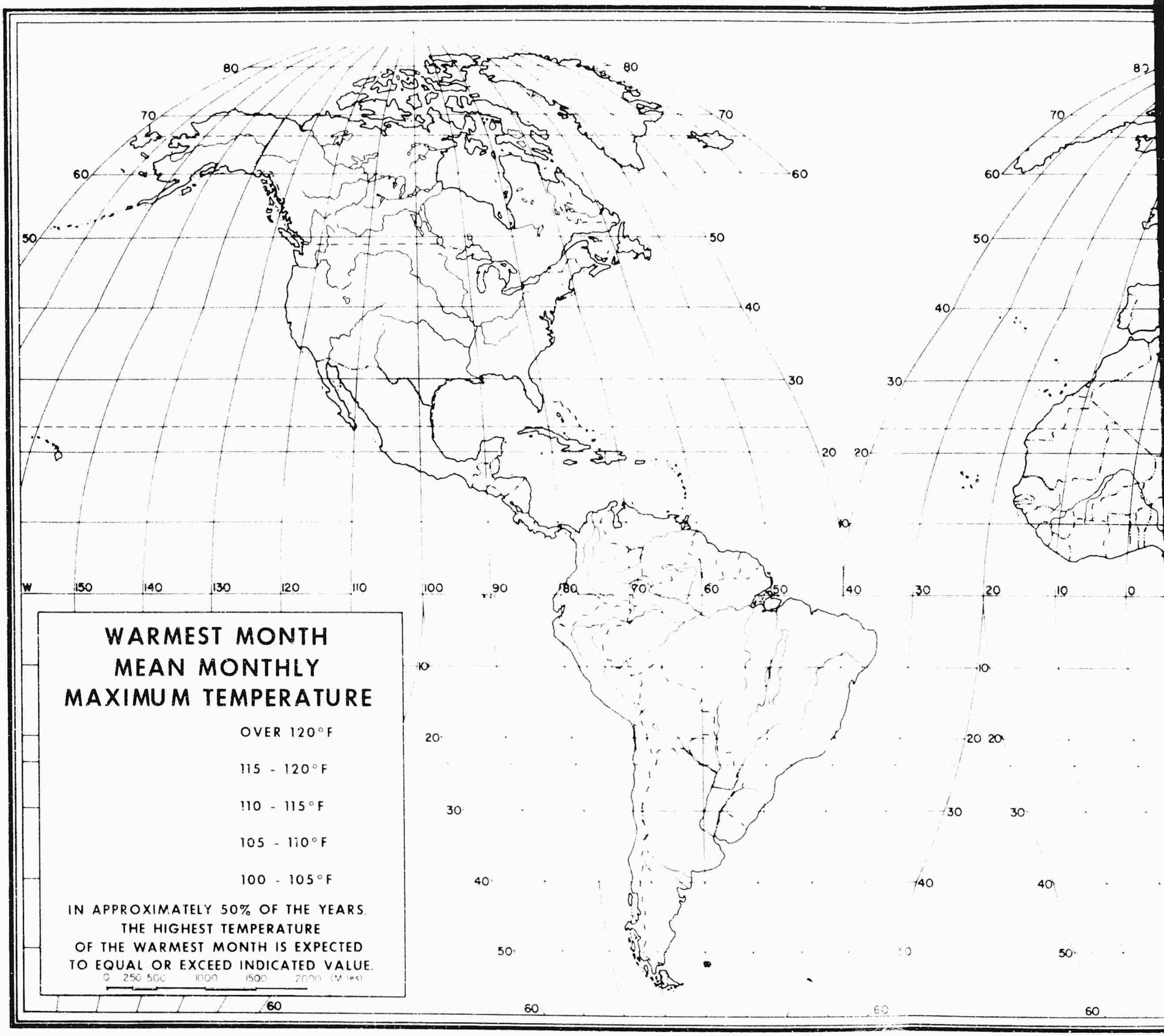
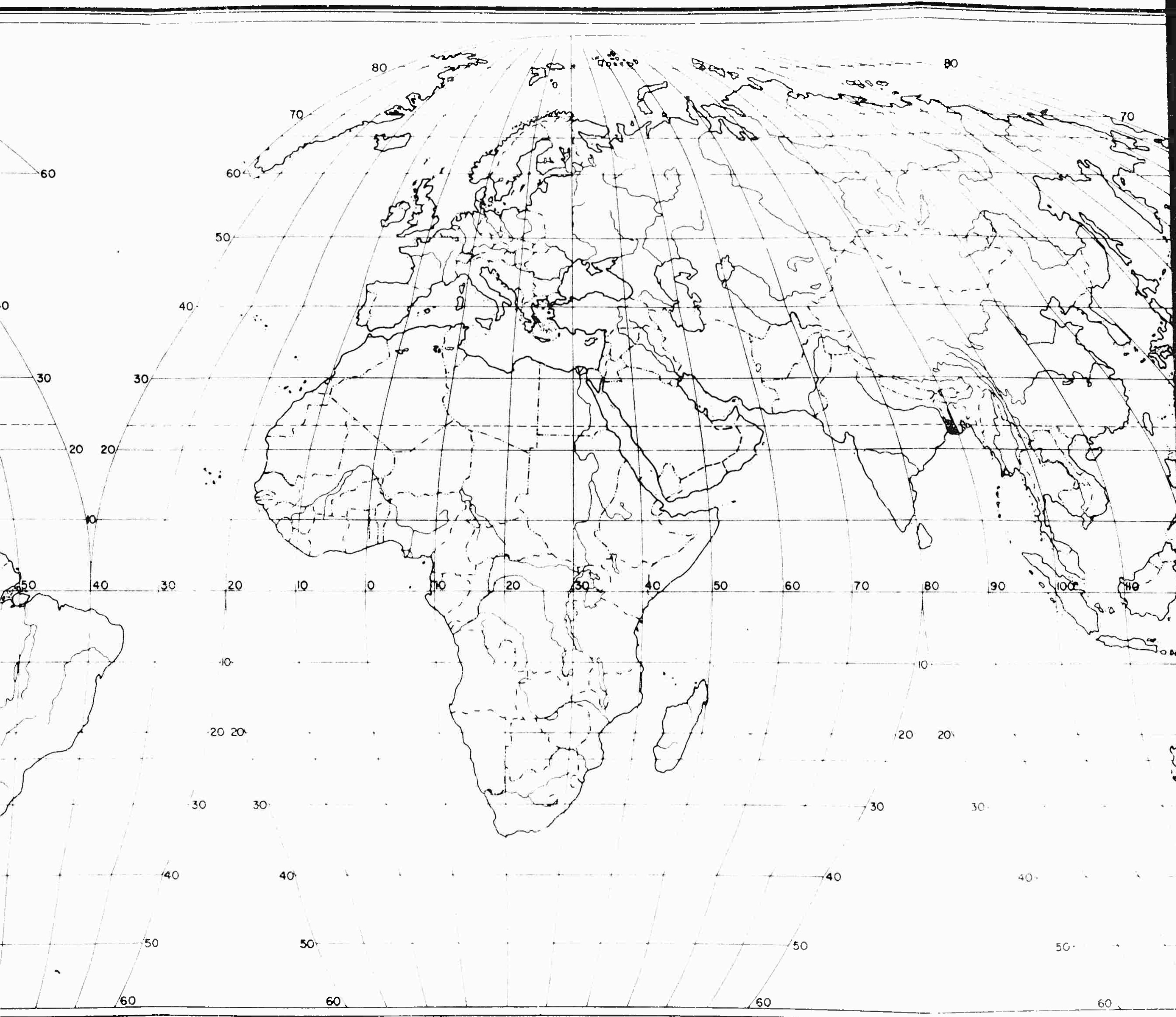

WARMEST MONTH
MEAN MONTHLY
MAXIMUM TEMPERATURE
OVER 120°F
115 - 120°F
110 - 115°F
105 - 110°F
100 - 105°F
IN APPROXIMATELY 50% OF THE YEARS, THE HIGHEST TEMPERATURE OF THE WARMEST MONTH IS EXPECTED TO EQUAL OR EXCEED INDICATED VALUE.
0 250 500 1000 1500 2000 (Miles)

Plate II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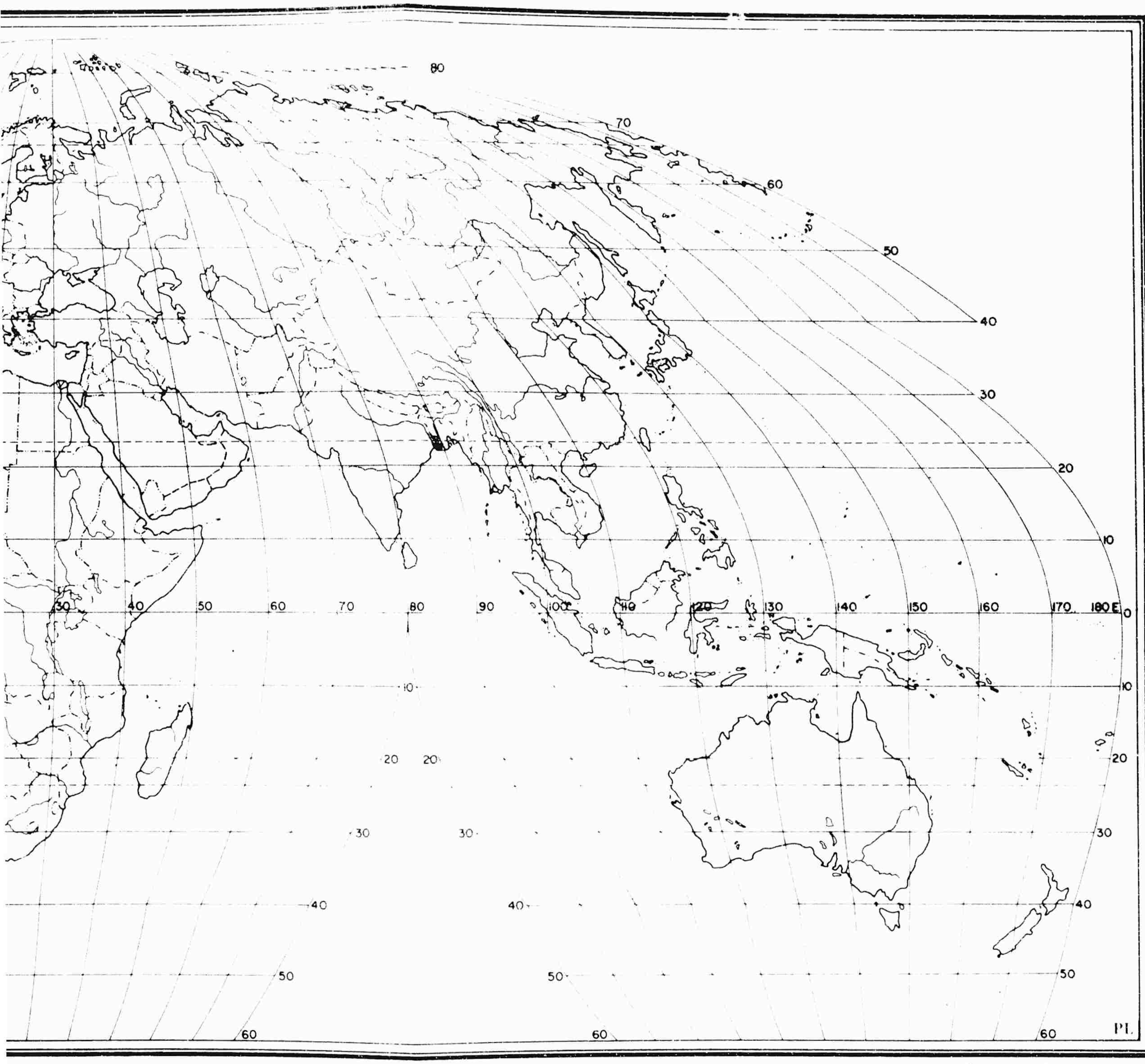
50 40 30 20 10 0 10 20 30 40 50 60 70 80 90 100 110



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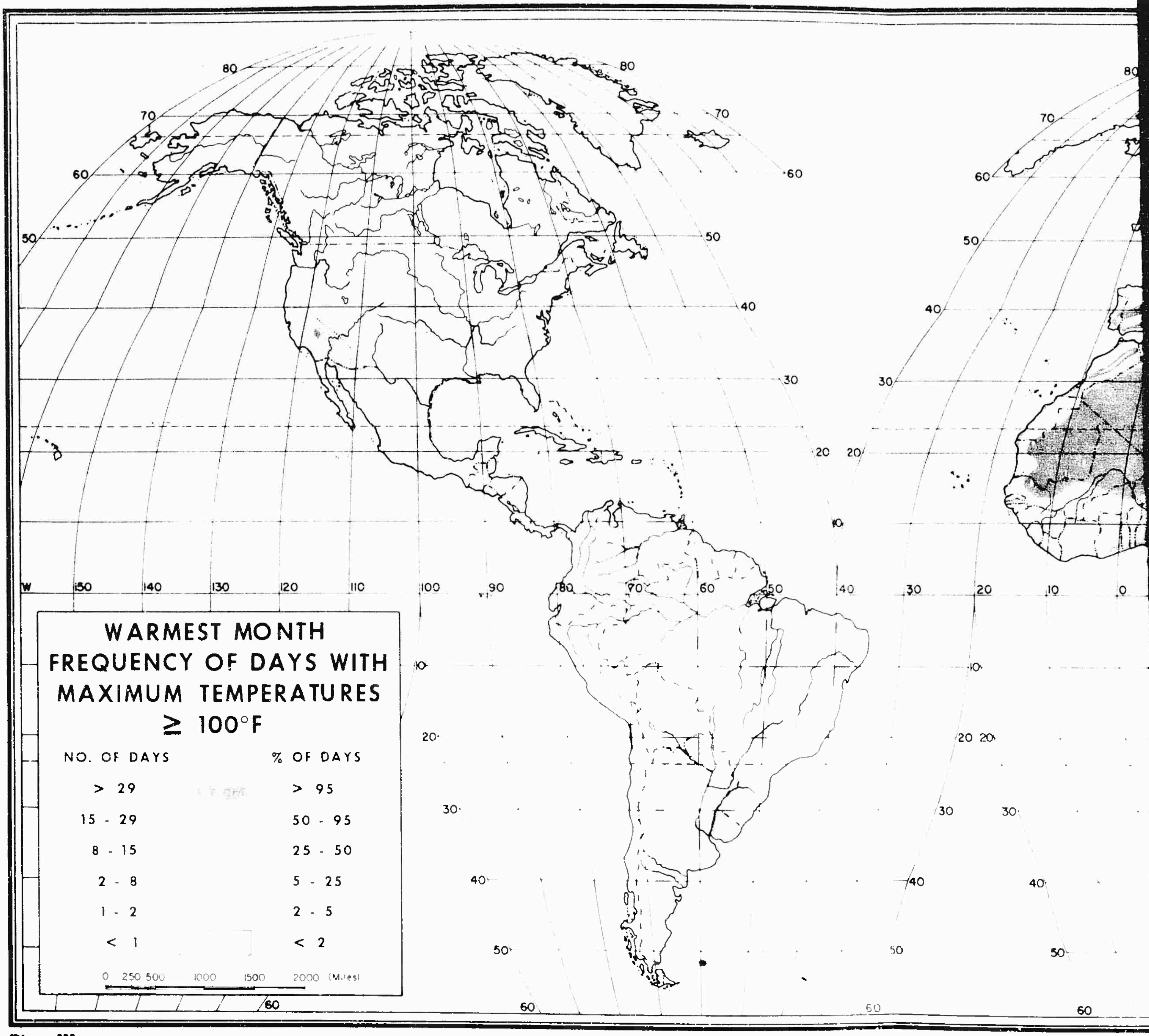
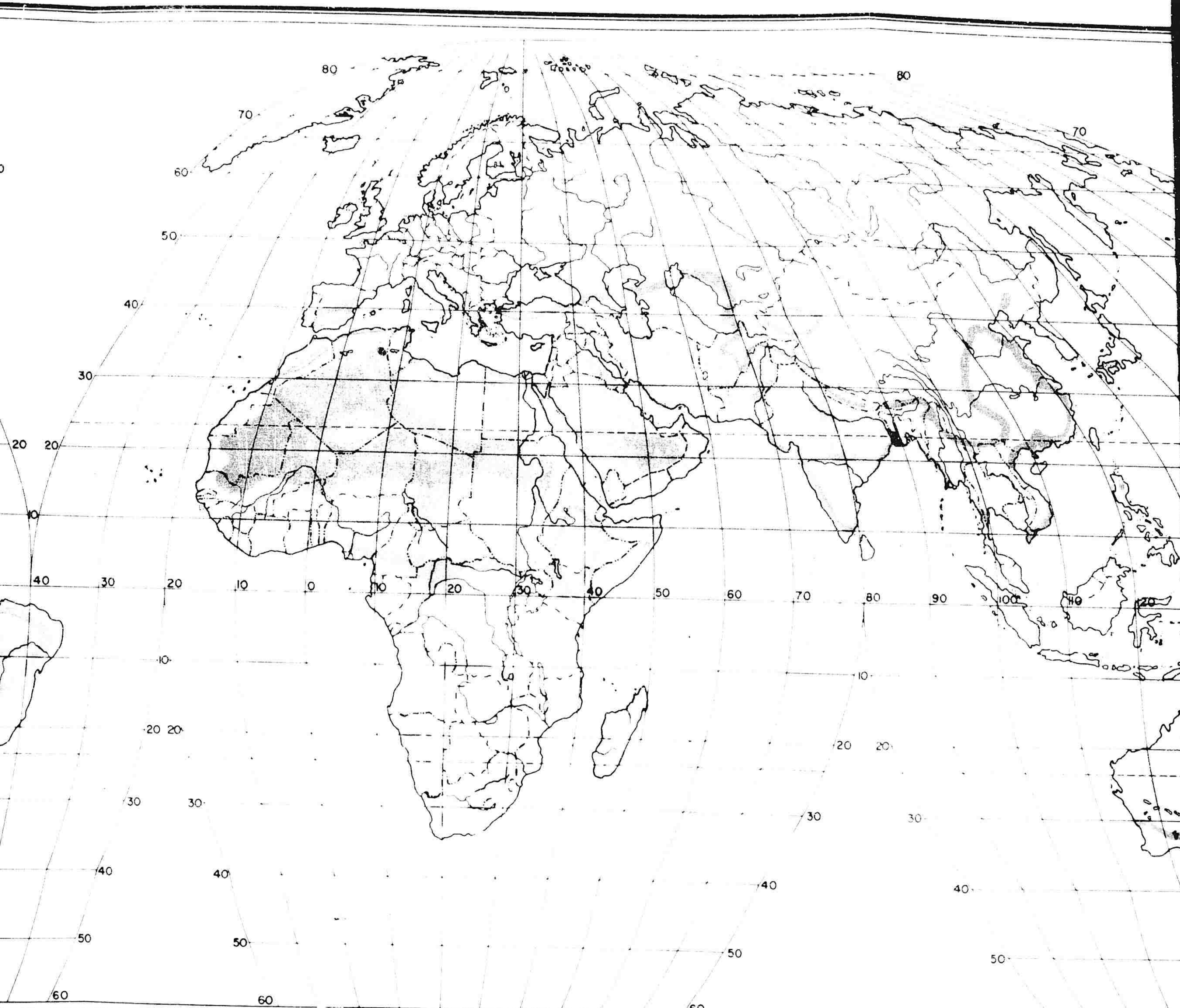

WARMEST MONTH
FREQUENCY OF DAYS WITH
MAXIMUM TEMPERATURES
≥ 100°F
NO. OF DAYS
% OF DAYS
> 29
> 95
15 - 29
50 - 95
8 - 15
25 - 50
2 - 8
5 - 25
1 - 2
2 - 5
< 1
< 2
0 250 500 1000 1500 2000 (Miles)

Plate III



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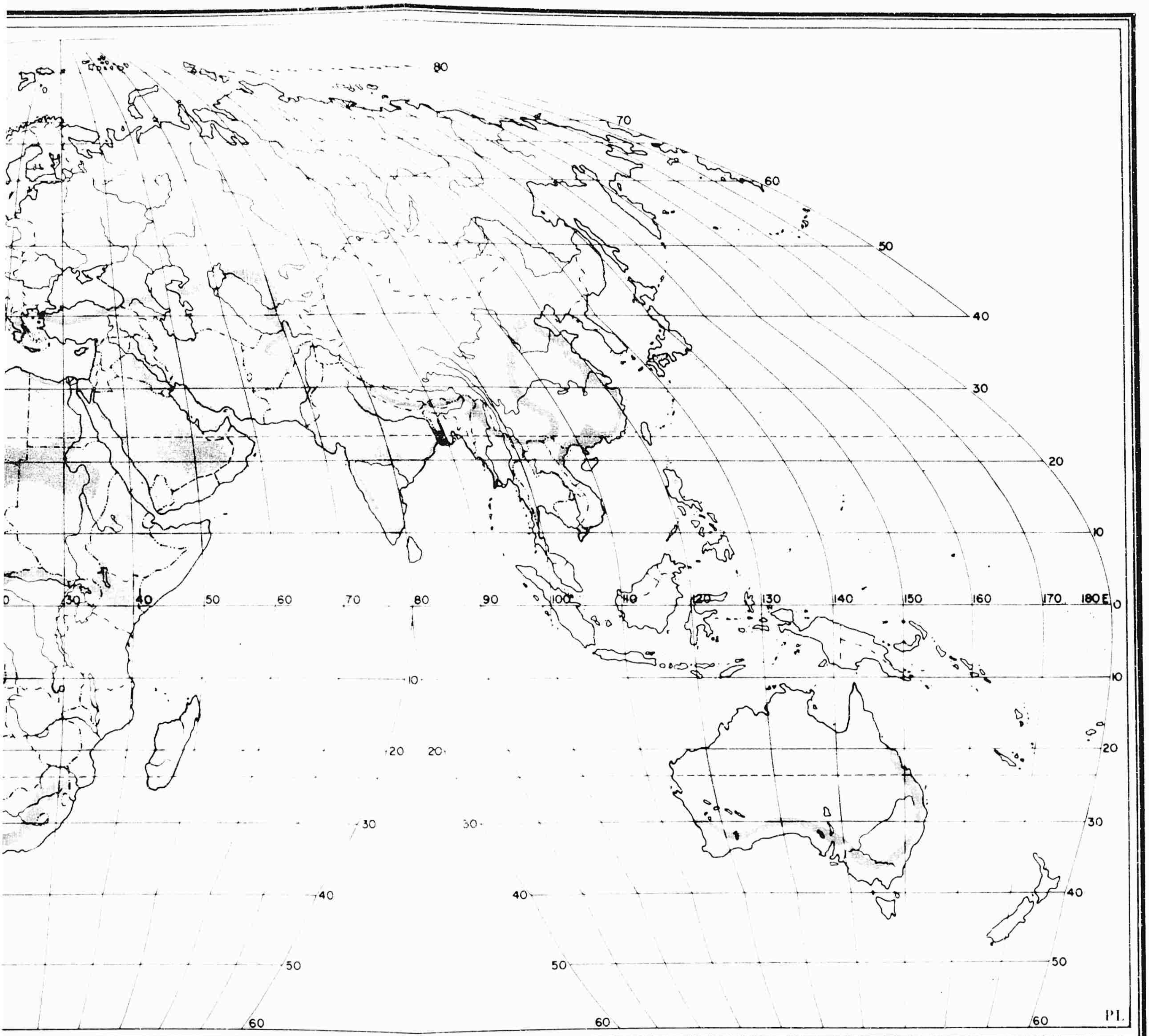

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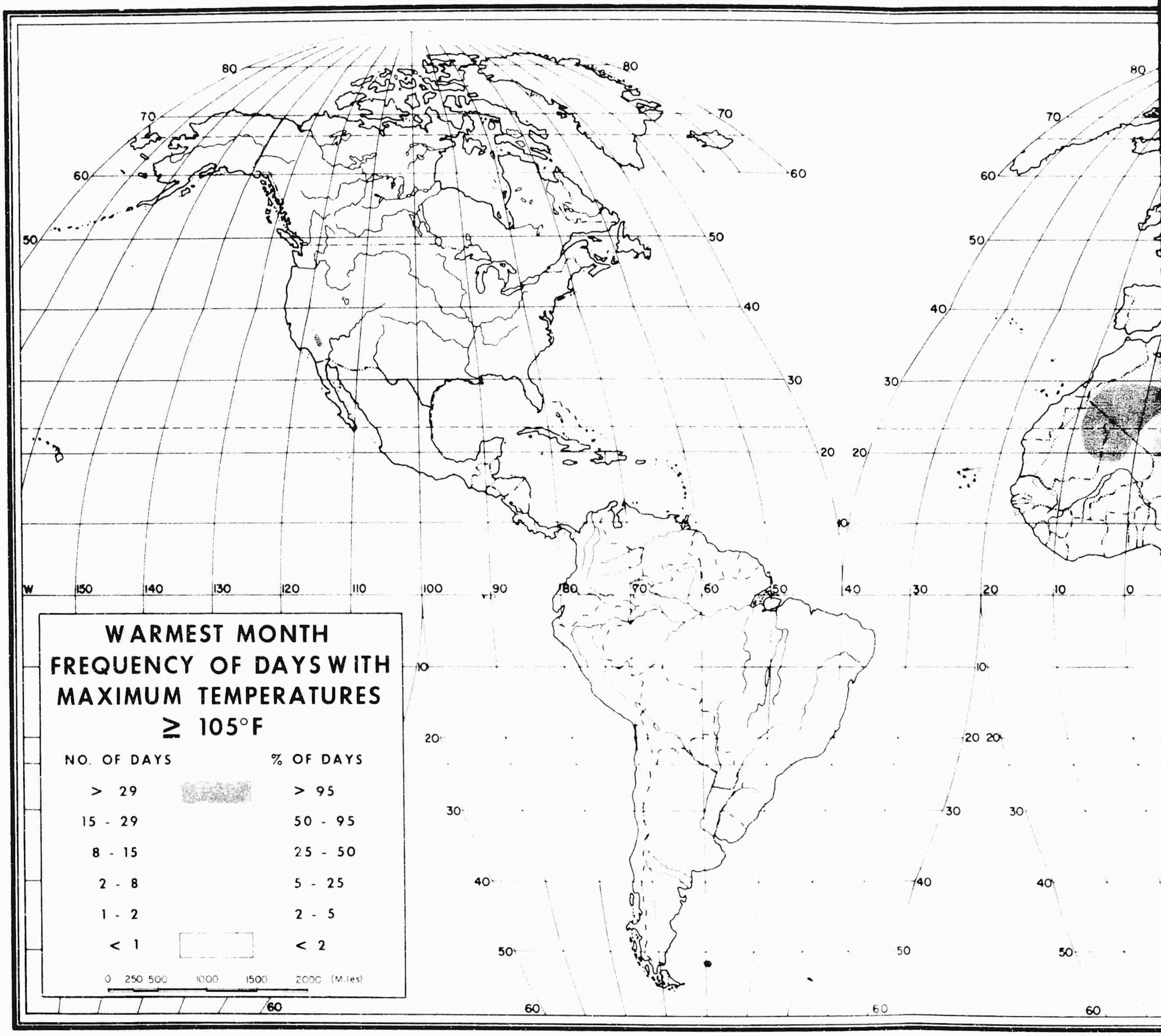
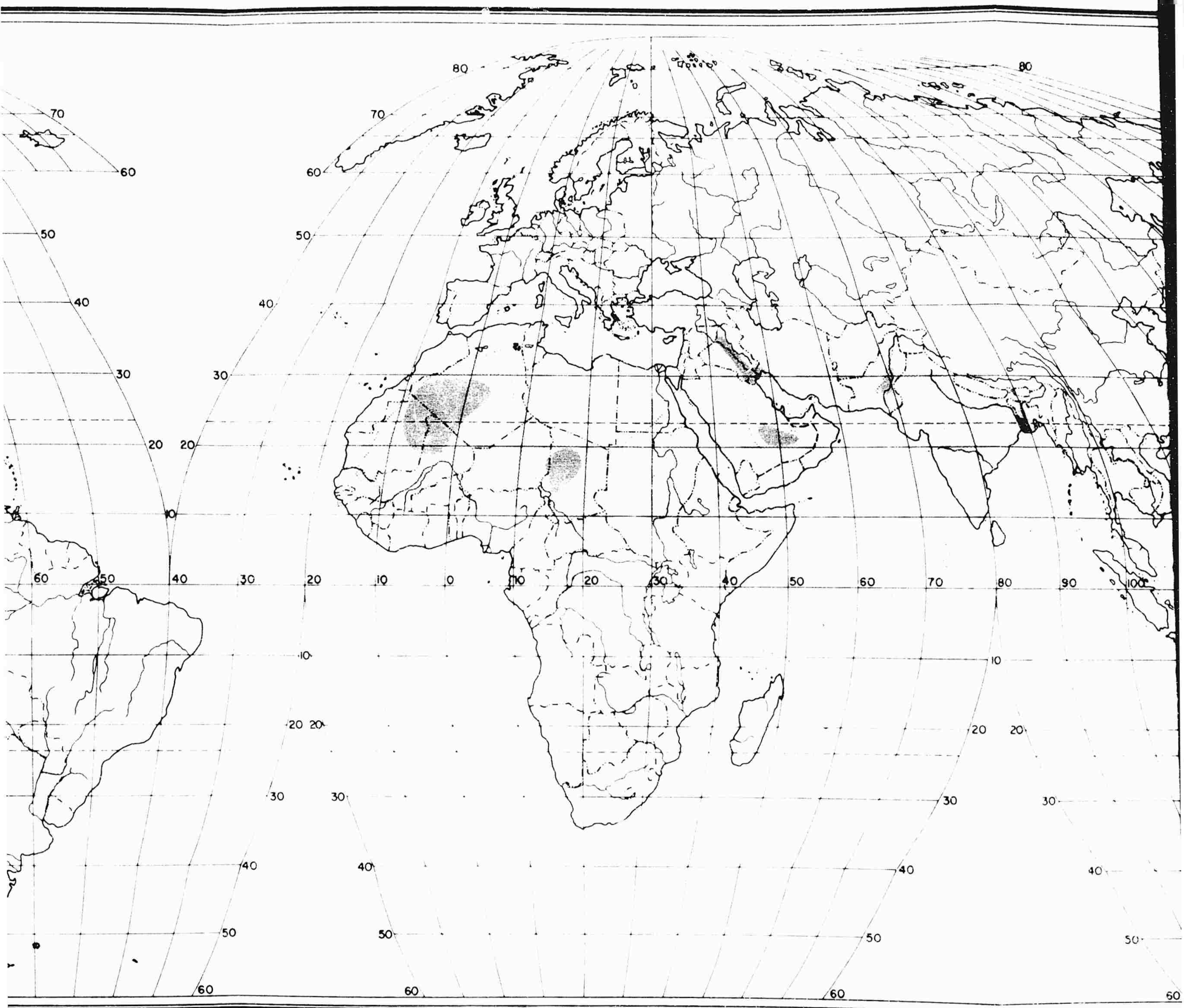

WARMEST MONTH
FREQUENCY OF DAYS WITH
MAXIMUM TEMPERATURES
≥ 105°F
NO. OF DAYS
% OF DAYS
> 29
> 95
15 - 29
50 - 95
8 - 15
25 - 50
2 - 8
5 - 25
1 - 2
2 - 5
< 1
< 2
0 250 500 1000 1500 2000 (Miles)

Plate IV



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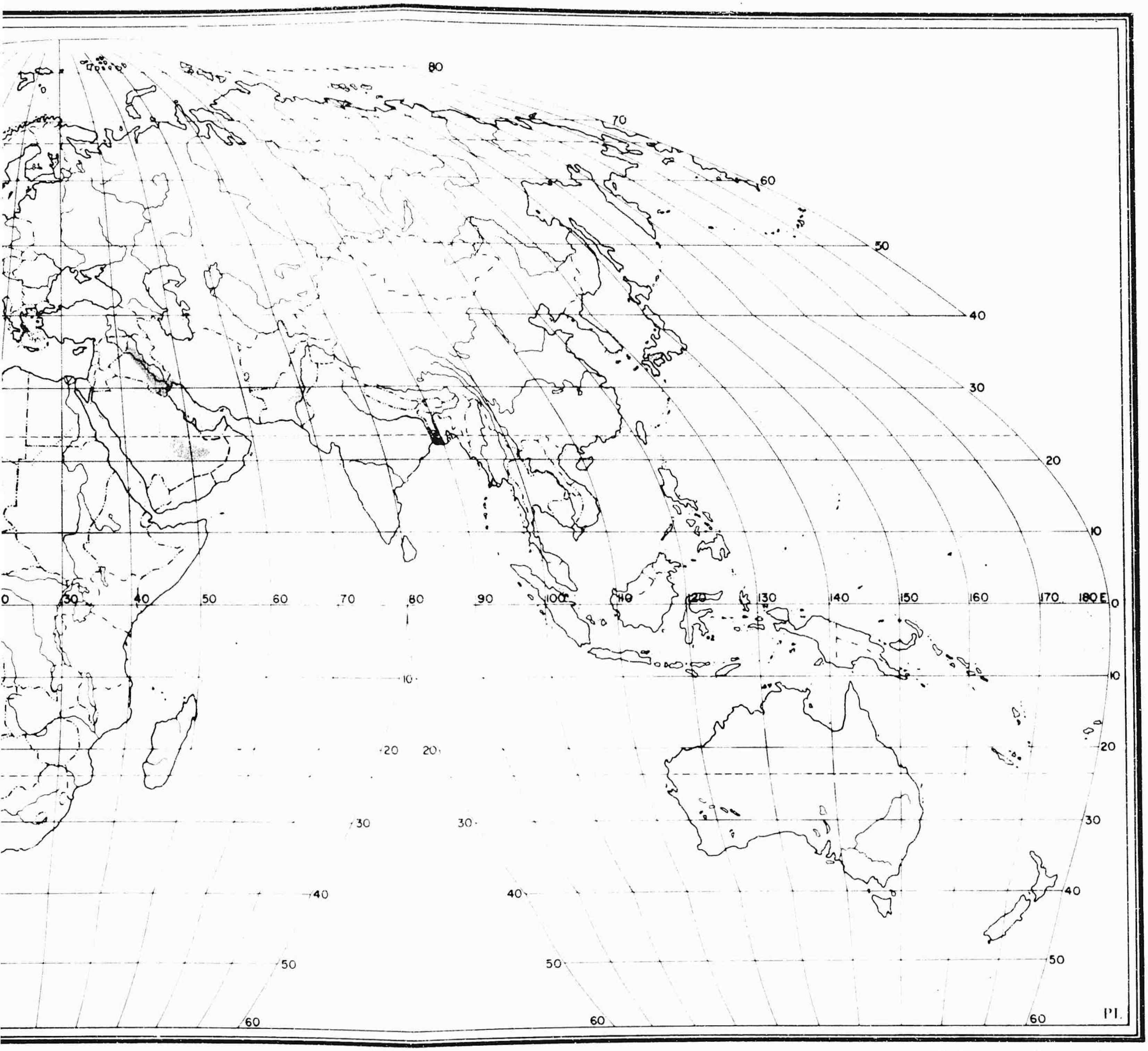
60

2



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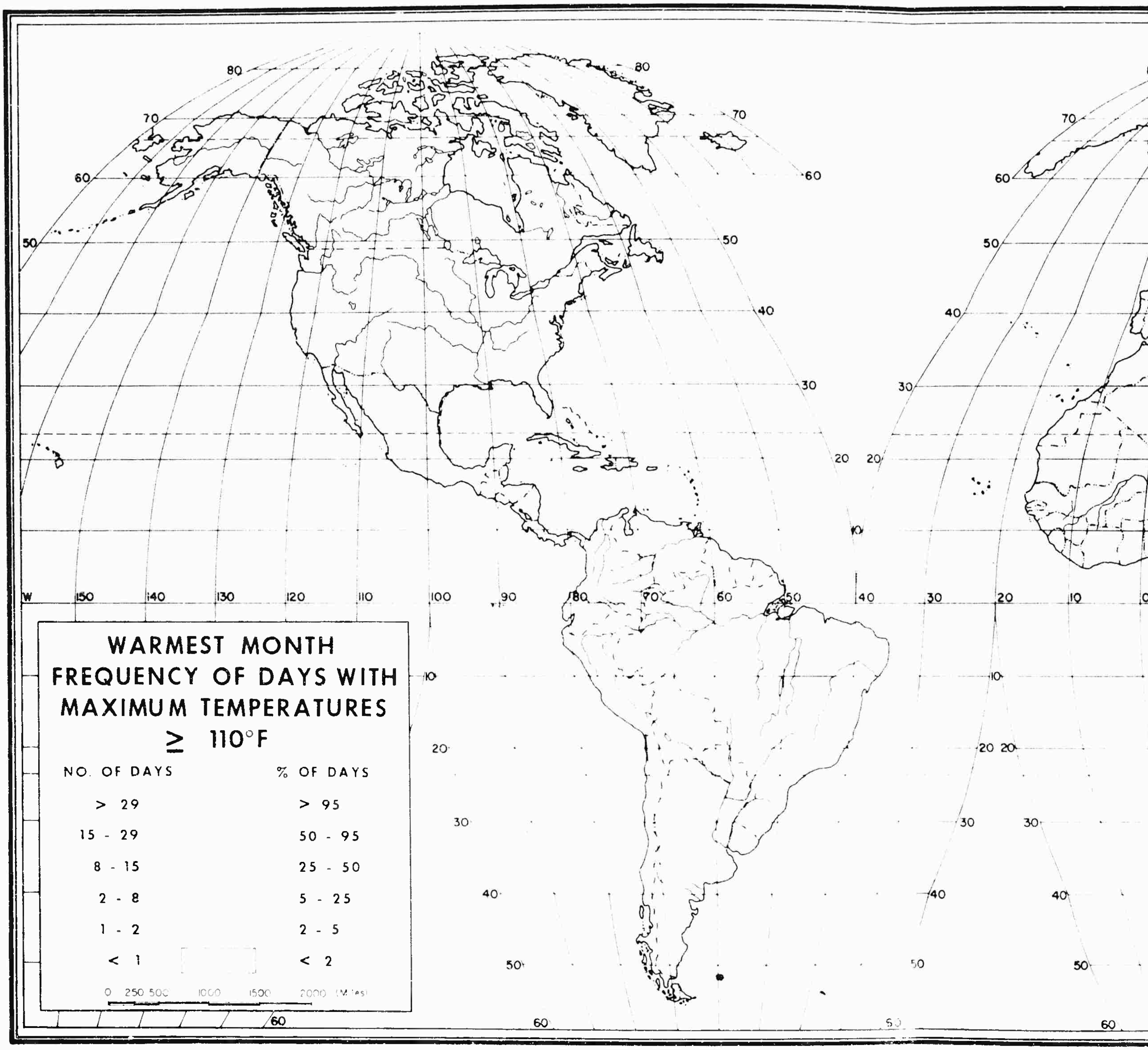
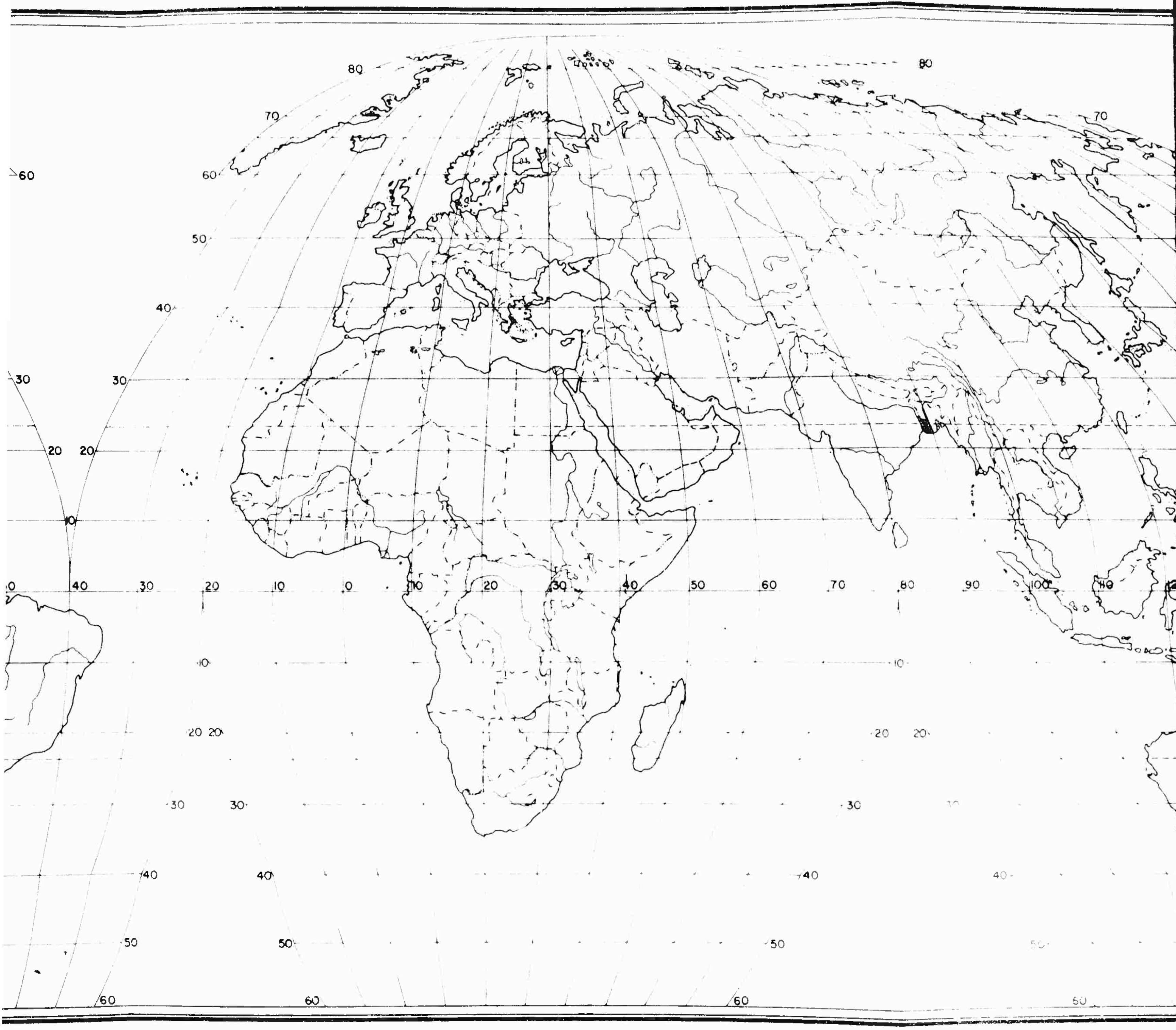

WARMEST MONTH
FREQUENCY OF DAYS WITH
MAXIMUM TEMPERATURES
≥ 110°F
NO. OF DAYS
% OF DAYS
> 29
> 95
15 - 29
50 - 95
8 - 15
25 - 50
2 - 8
5 - 25
1 - 2
2 - 5
< 1
< 2
0 250 500 1000 1500 2000 (Miles)

Plate V



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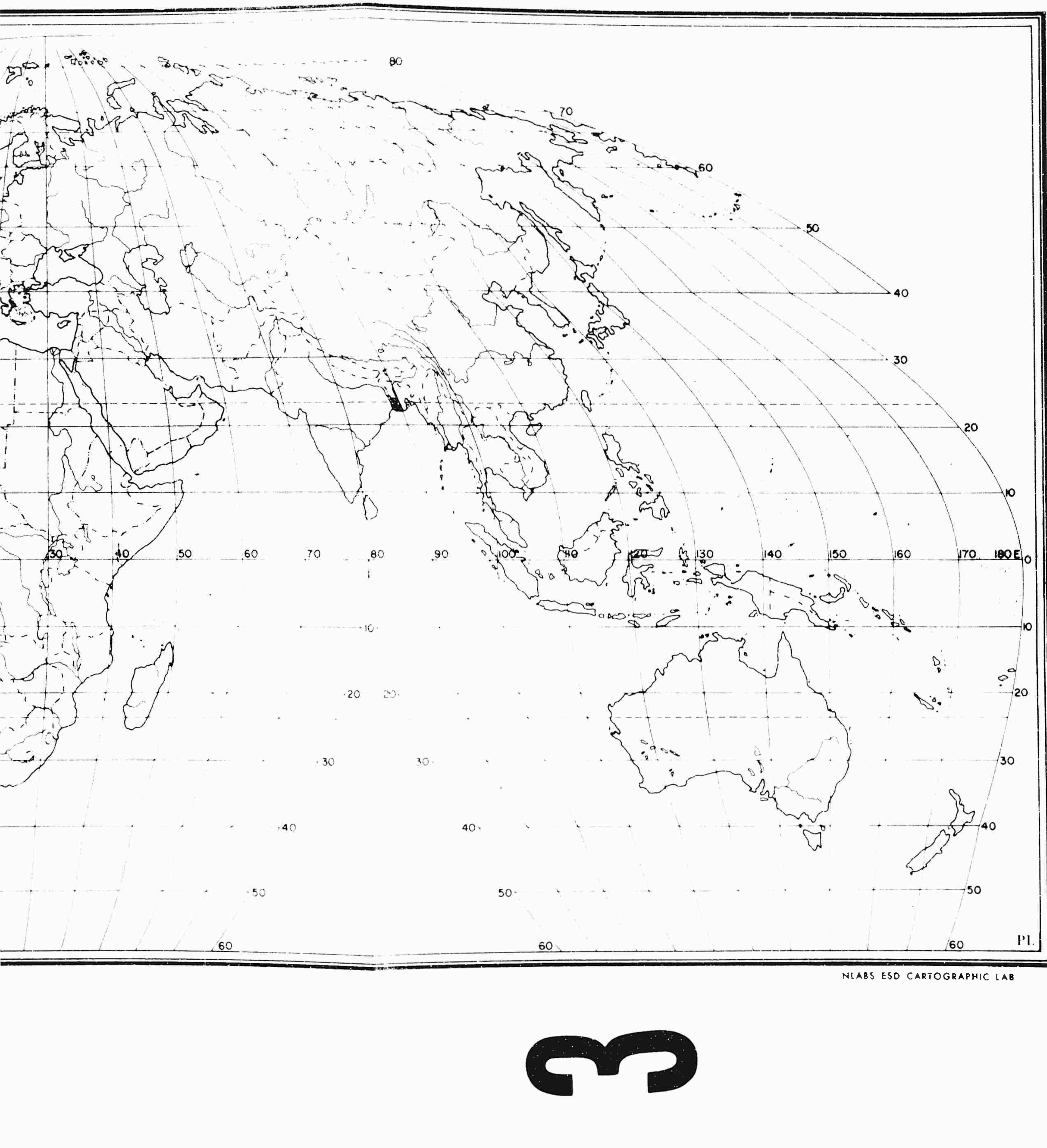

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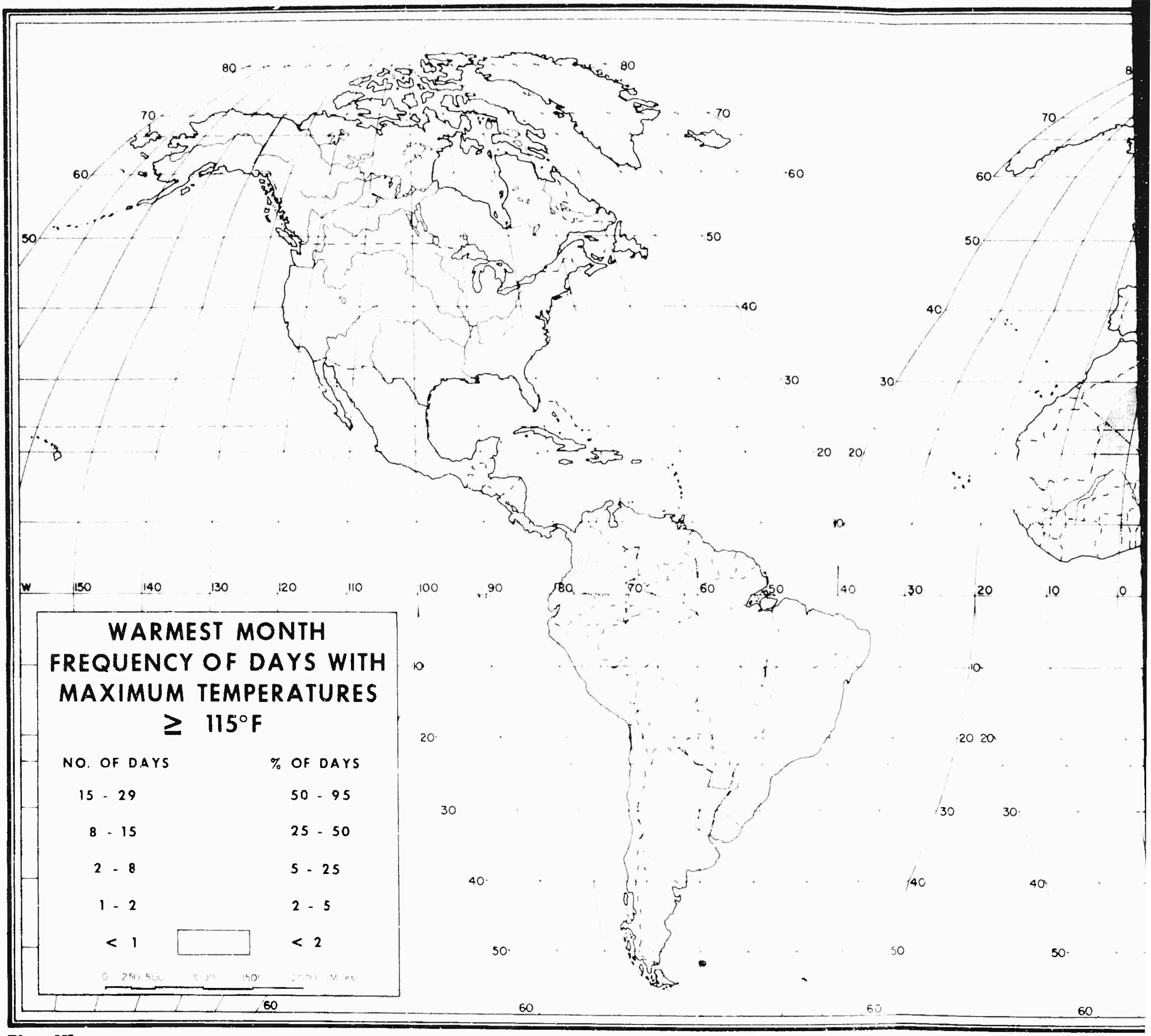
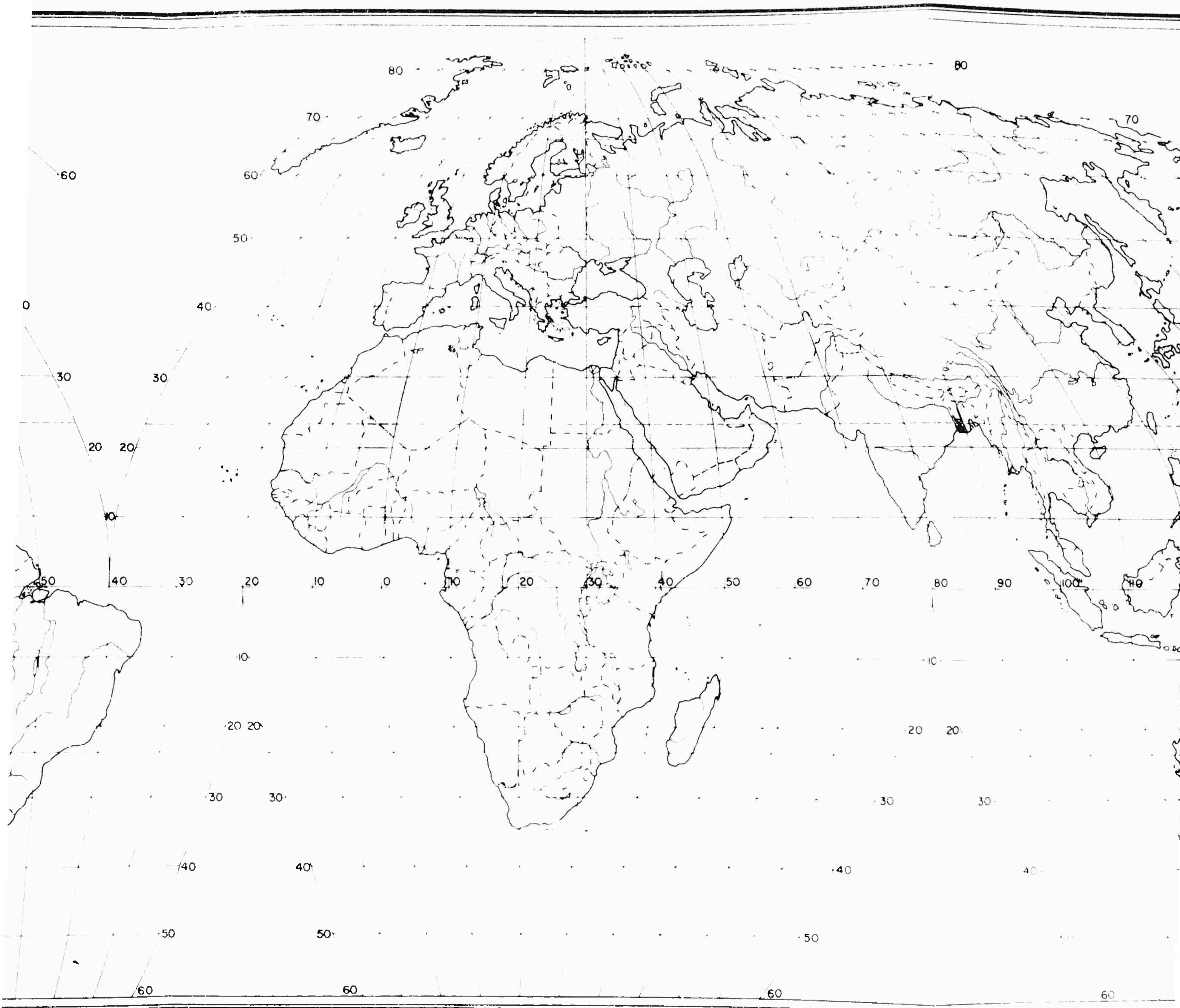

WARMEST MONTH
FREQUENCY OF DAYS WITH
MAXIMUM TEMPERATURES
≥ 115°F
NO. OF DAYS
% OF DAYS
15 - 29
50 - 95
8 - 15
25 - 50
2 - 8
5 - 25
1 - 2
2 - 5
< 1
< 2

Plate VI


80
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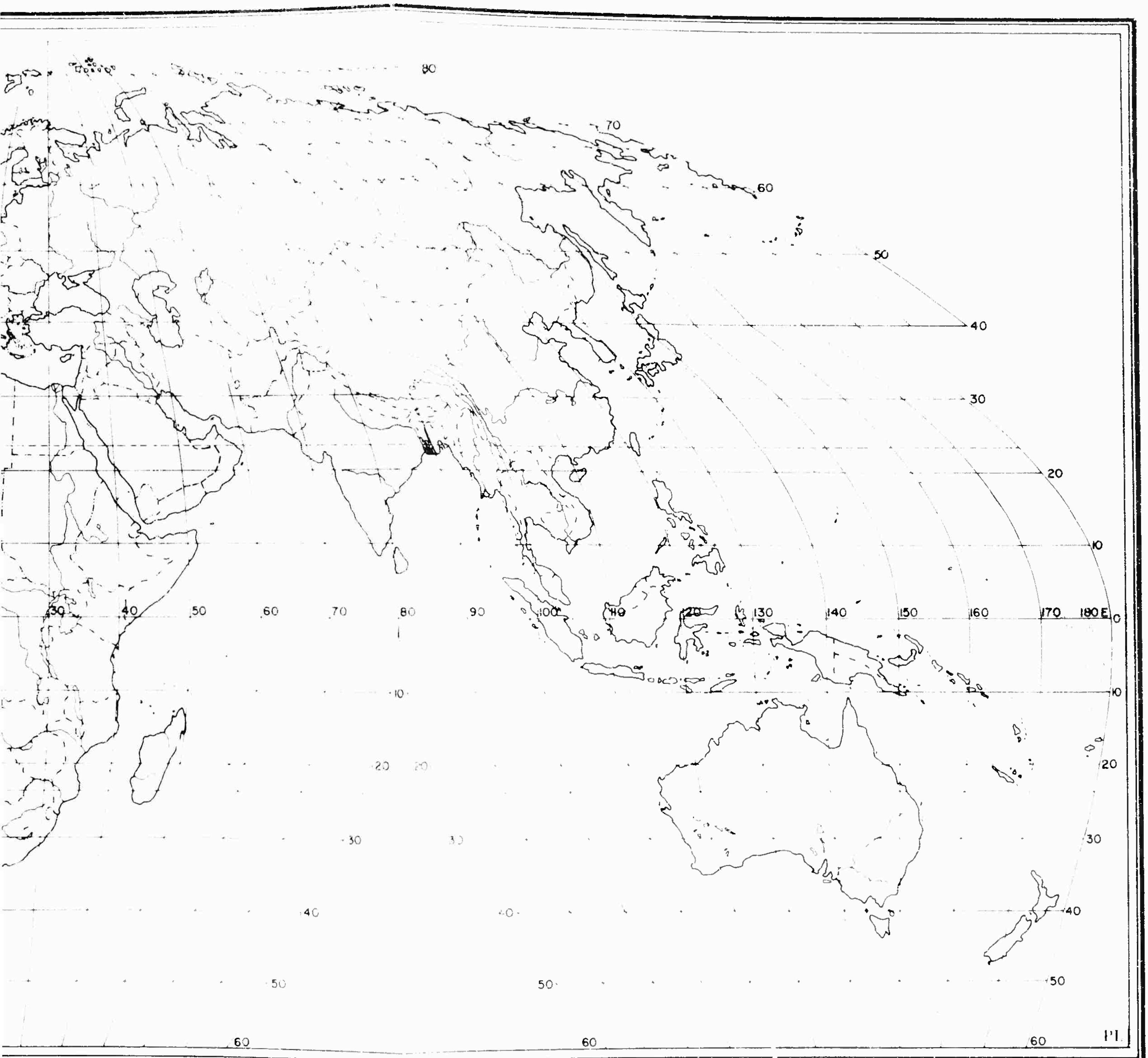
60

2



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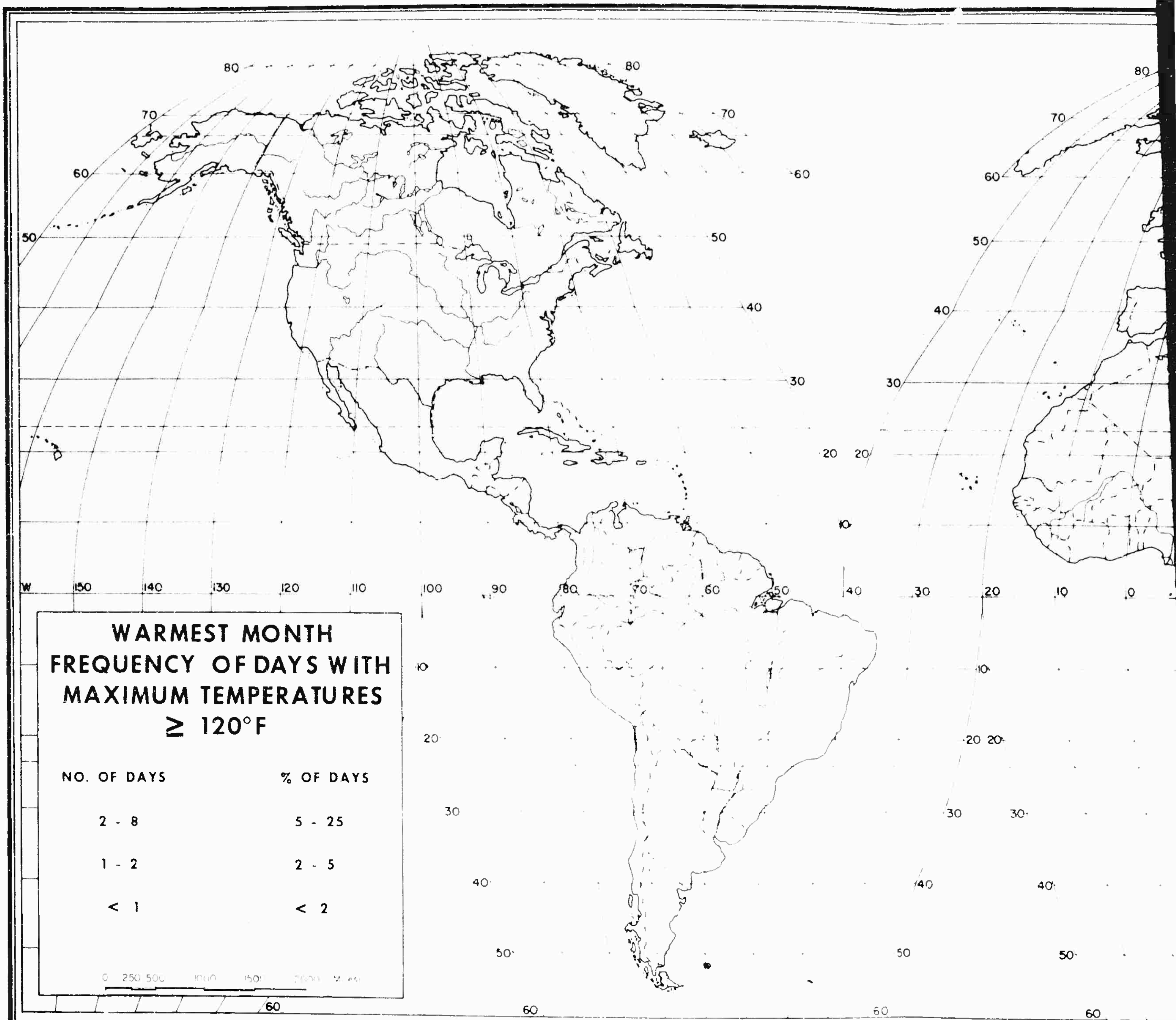
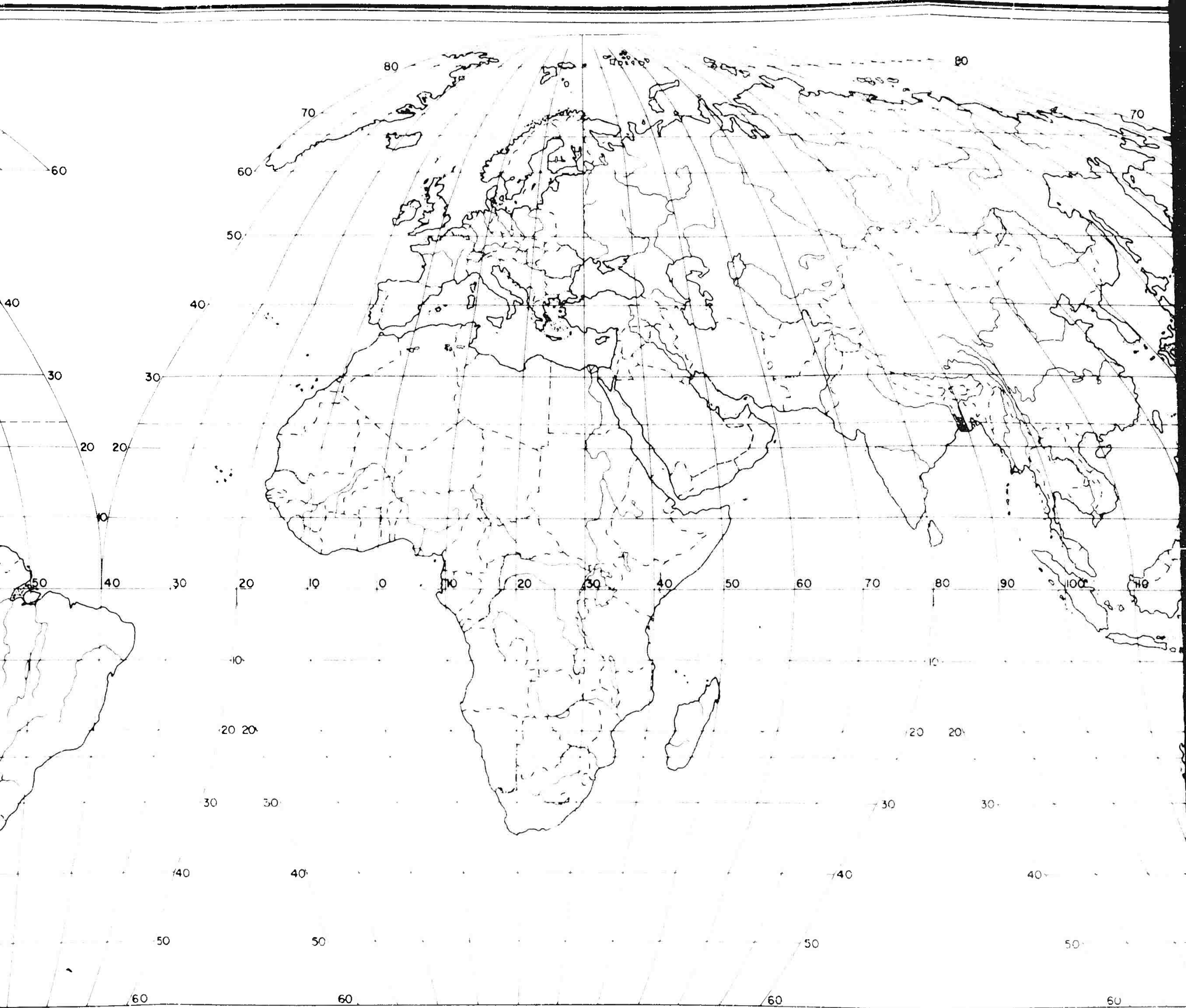


WARMEST MONTH
FREQUENCY OF DAYS WITH
MAXIMUM TEMPERATURES
≥ 120°F
NO. OF DAYS
% OF DAYS
2 - 8
5 - 25
1 - 2
2 - 5
< 1
< 2

Plate VII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40 30 20 10 0 10 20 30 40 50 60 70 80 90 100 110
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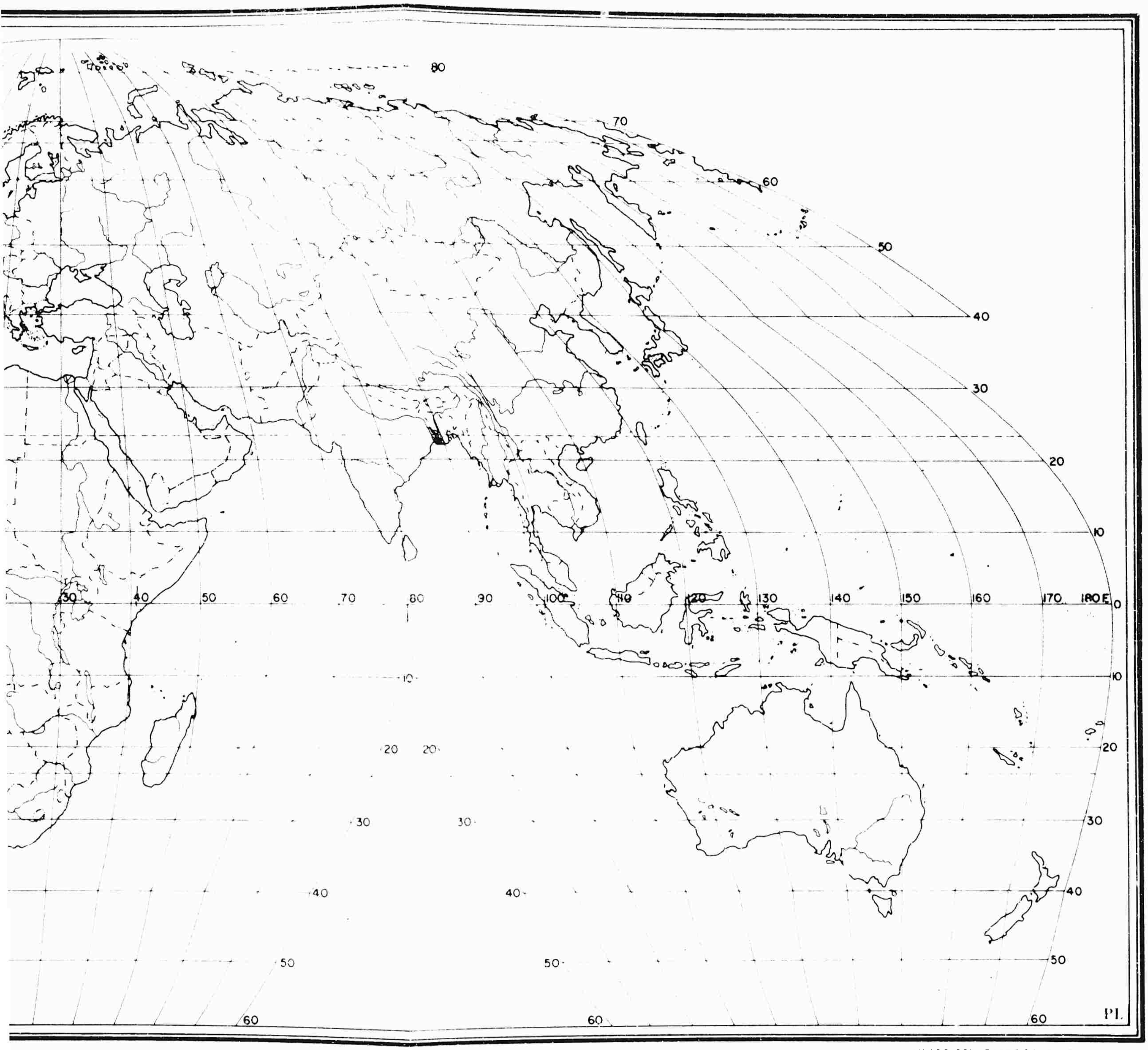
60

2



NLABS ESD CARTOGRAPHIC LAB

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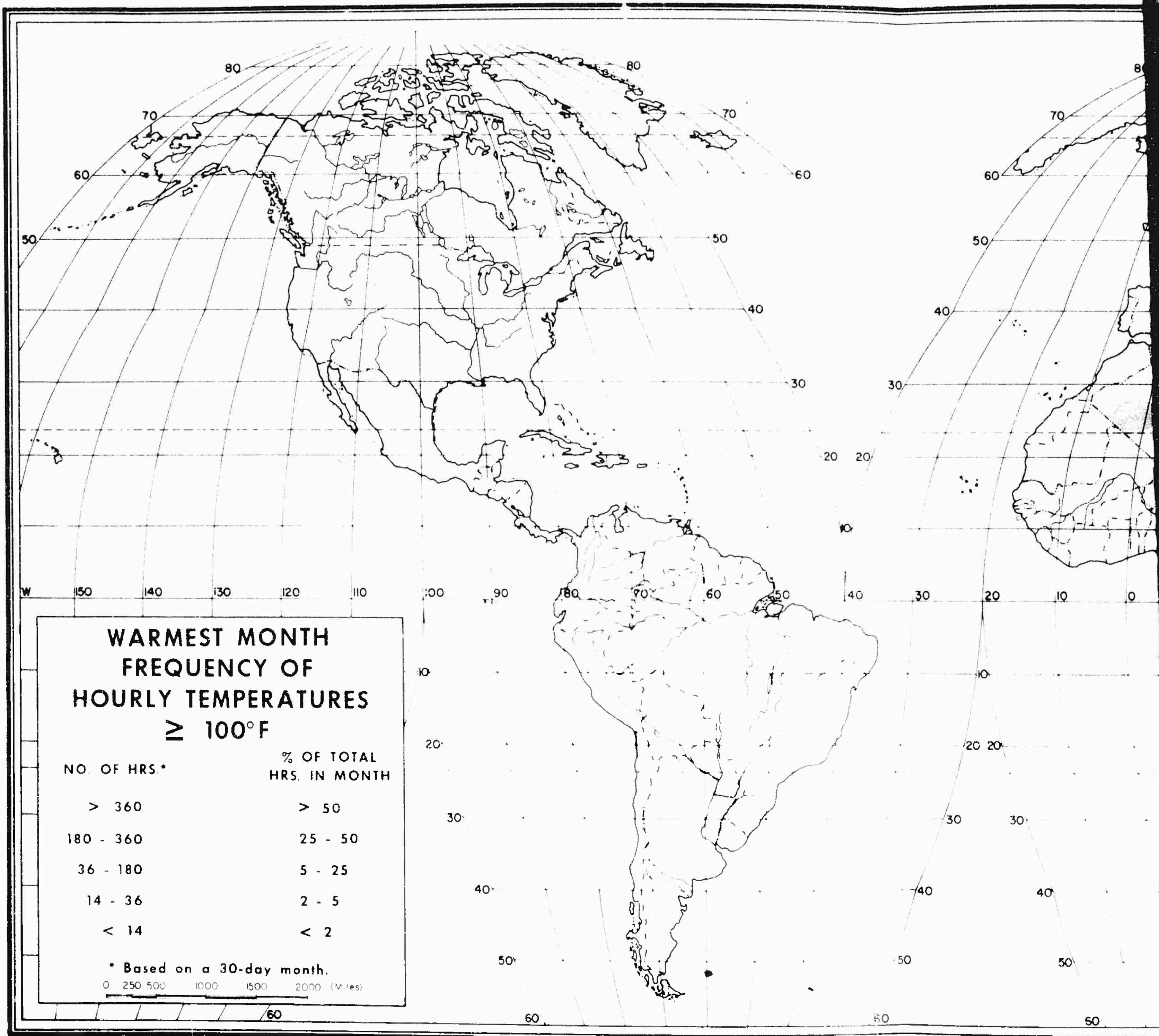
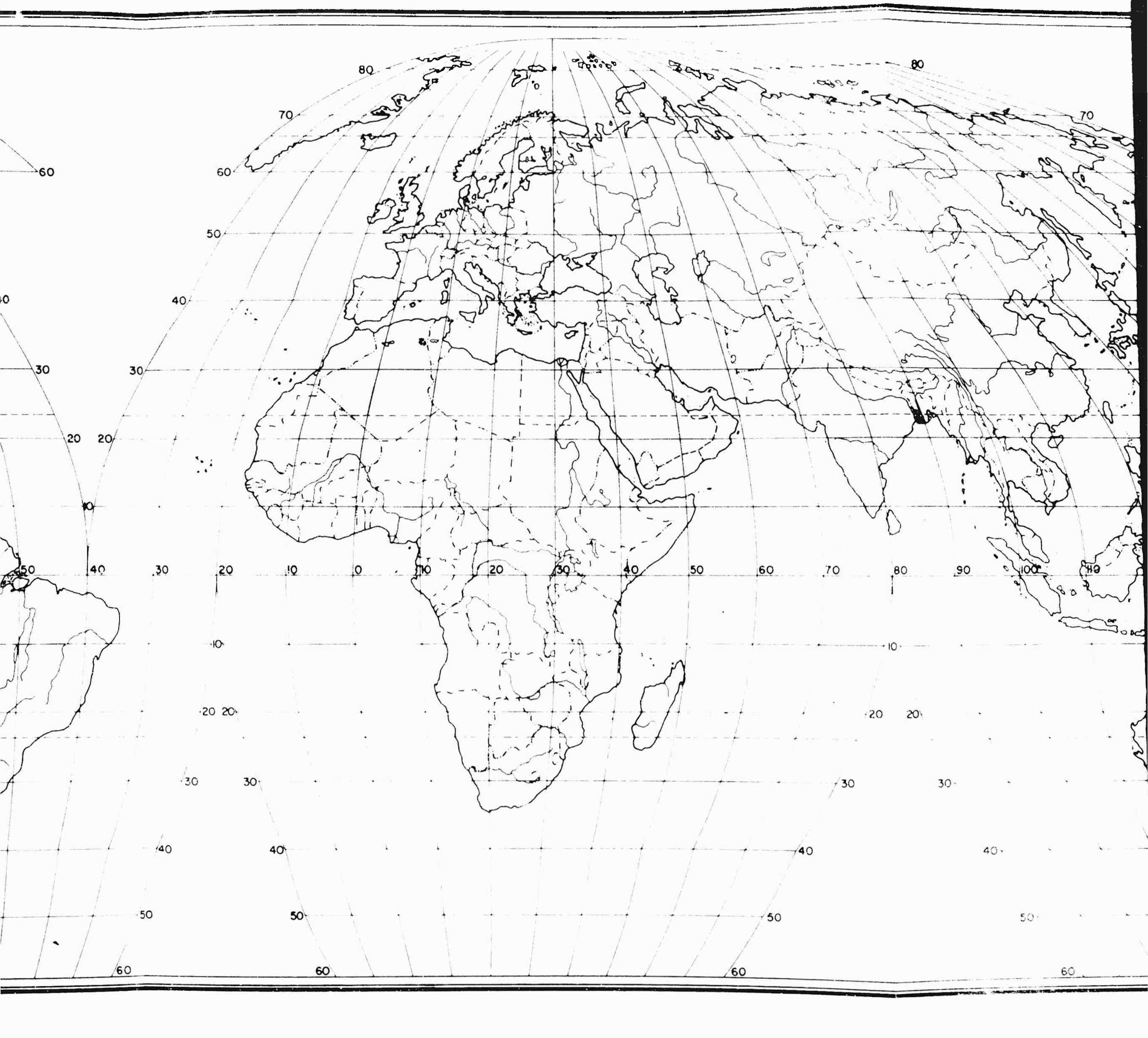

WARMEST MONTH
FREQUENCY OF
HOURLY TEMPERATURES
≥ 100°F
NO. OF HRS.*
% OF TOTAL HRS. IN MONTH
> 360
> 50
180 - 360
25 - 50
36 - 180
5 - 25
14 - 36
2 - 5
< 14
< 2
* Based on a 30-day month.
0 250 500 1000 1500 2000 (Miles)

Plate VIII



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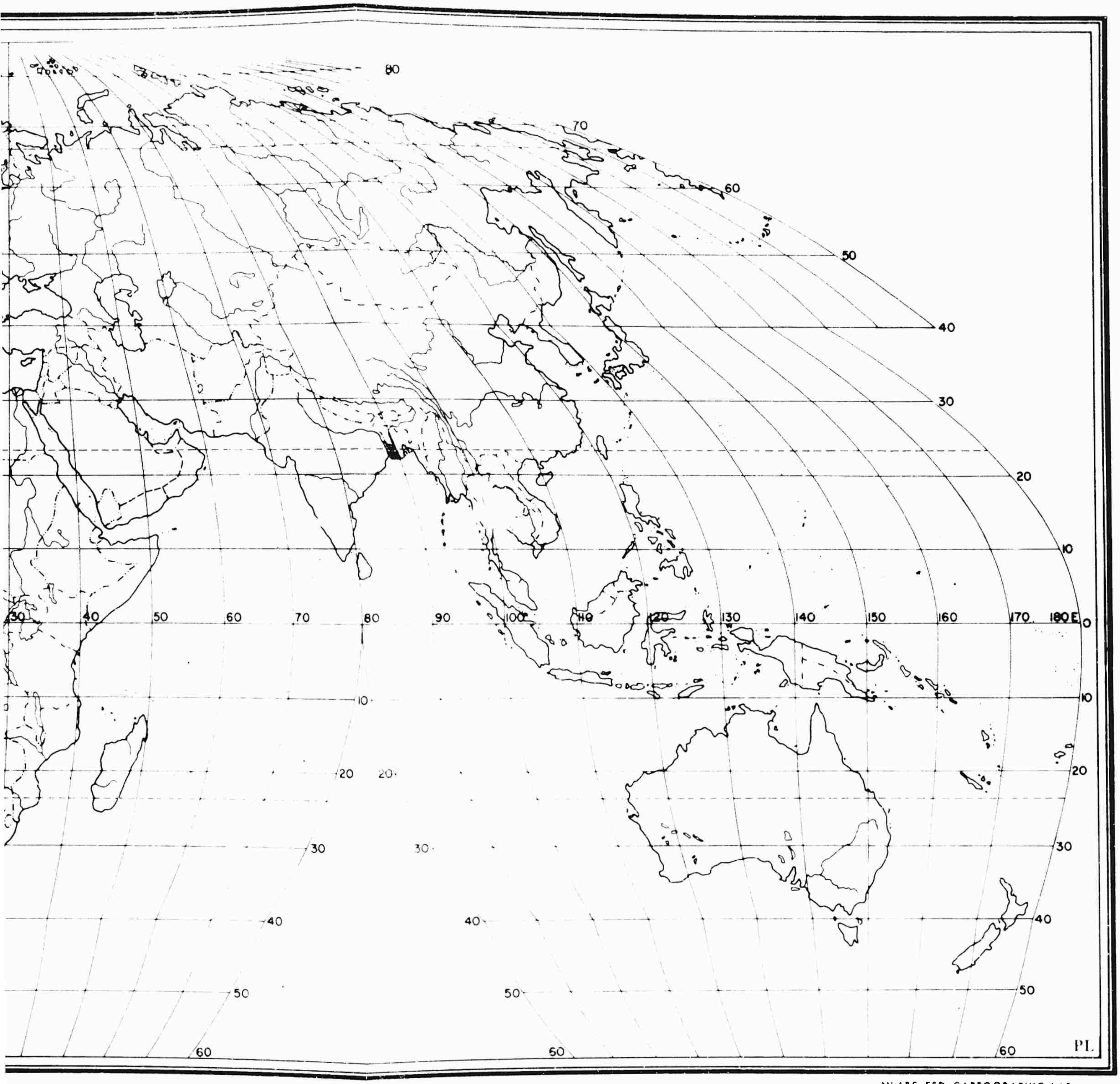

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3

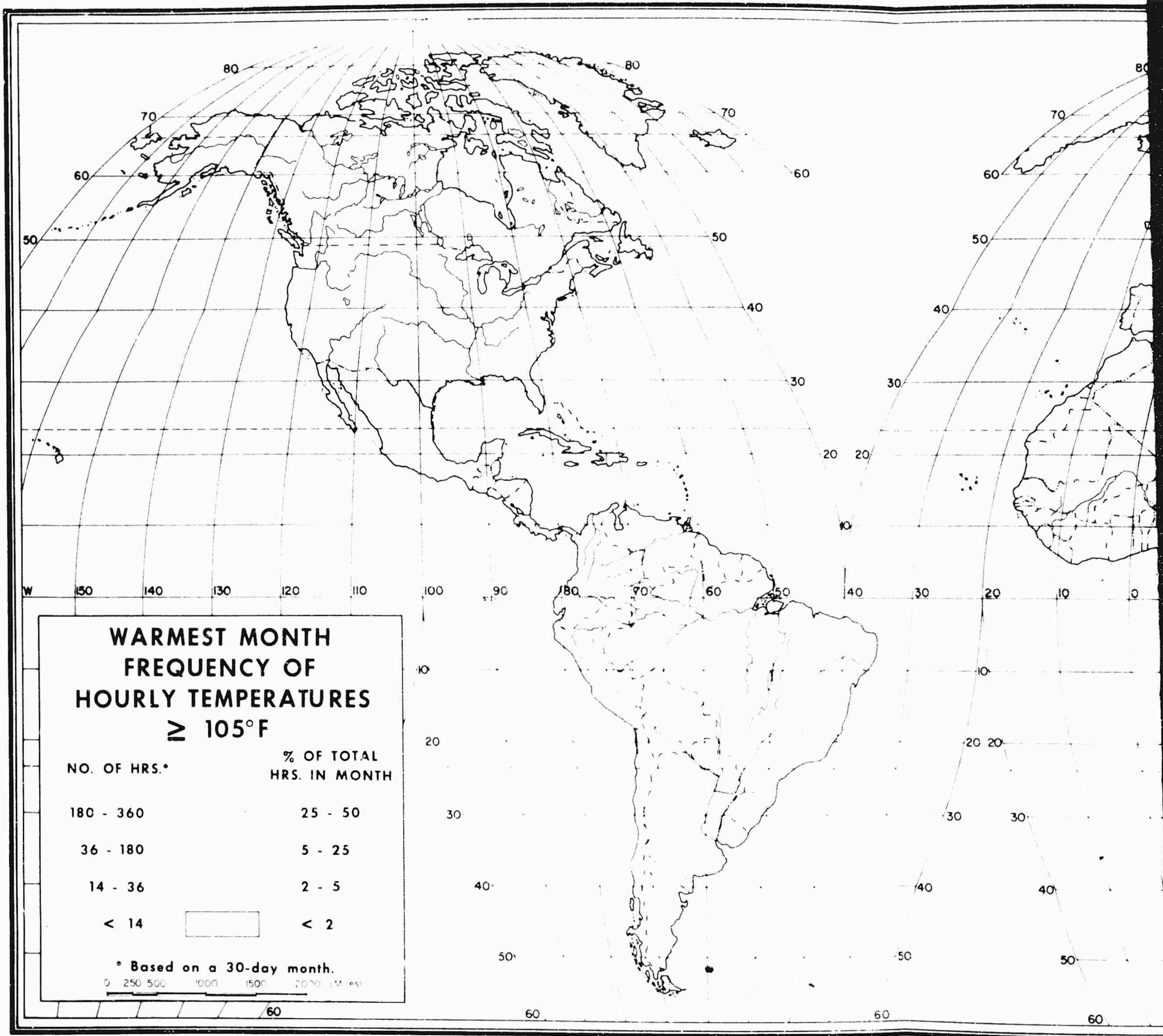
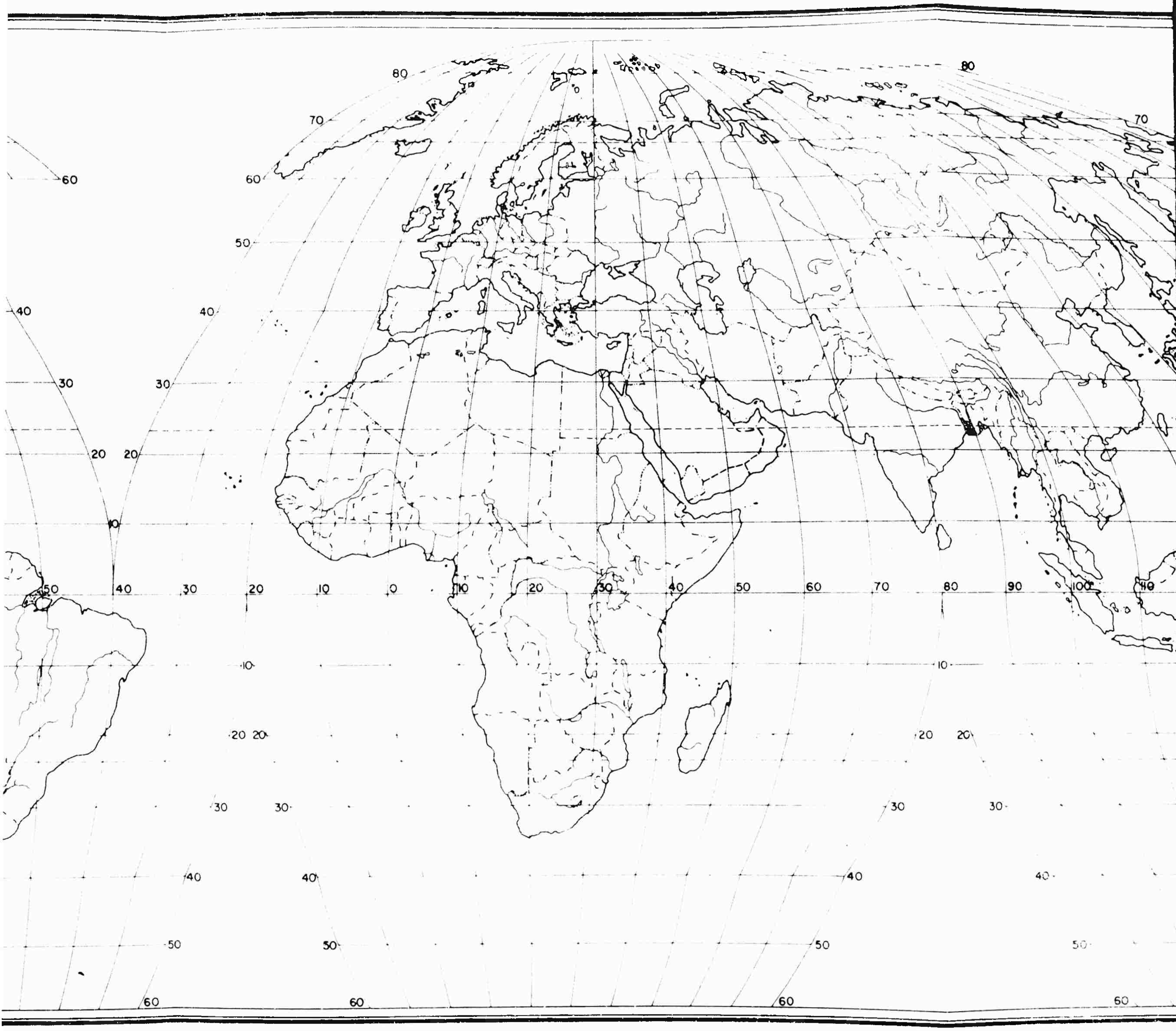

WARMEST MONTH
FREQUENCY OF
HOURLY TEMPERATURES
≥ 105°F
NO. OF HRS.*
% OF TOTAL HRS. IN MONTH
180 - 360
25 - 50
36 - 180
5 - 25
14 - 36
2 - 5
< 14
< 2
* Based on a 30-day month.

Plate IX



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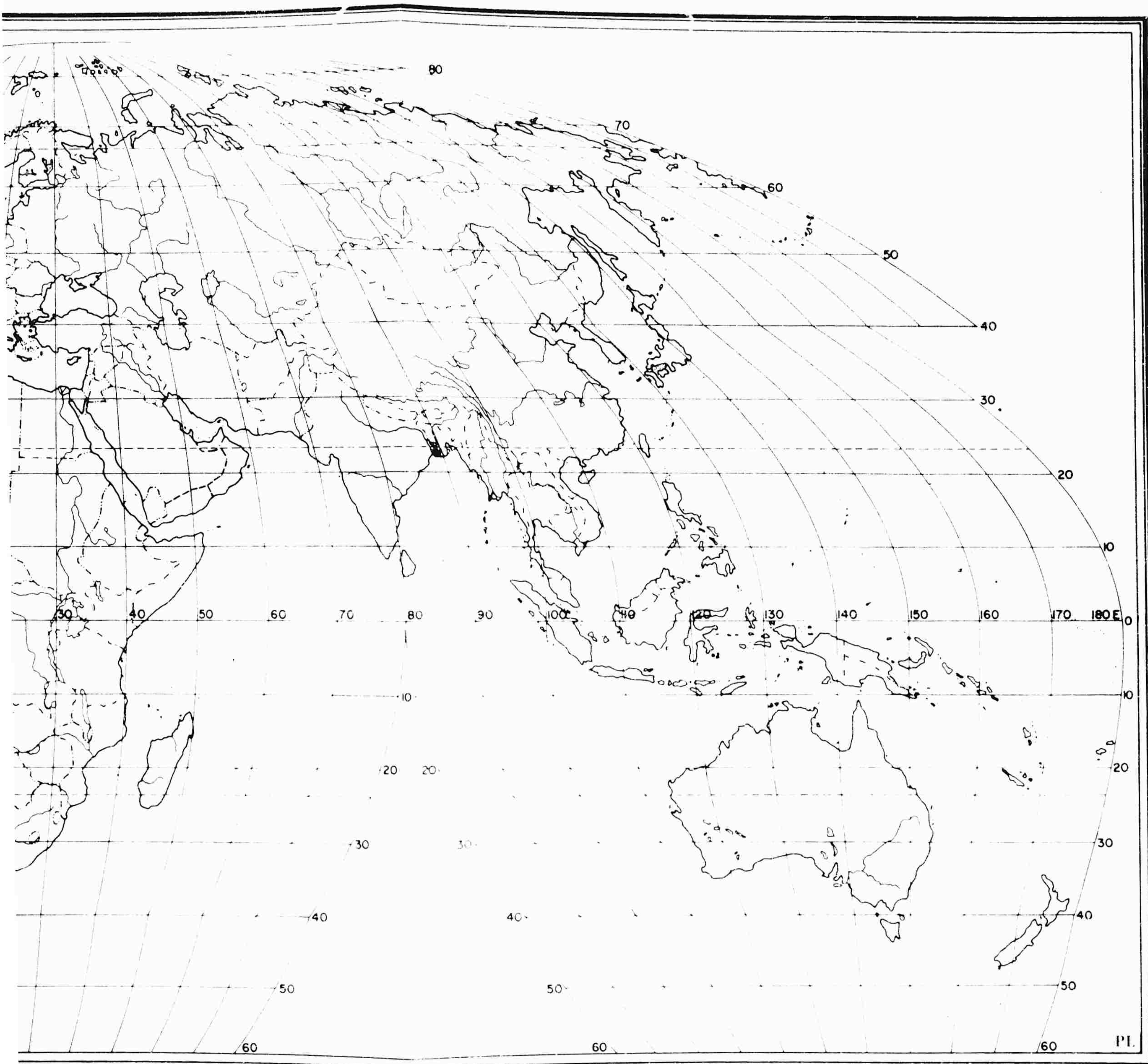

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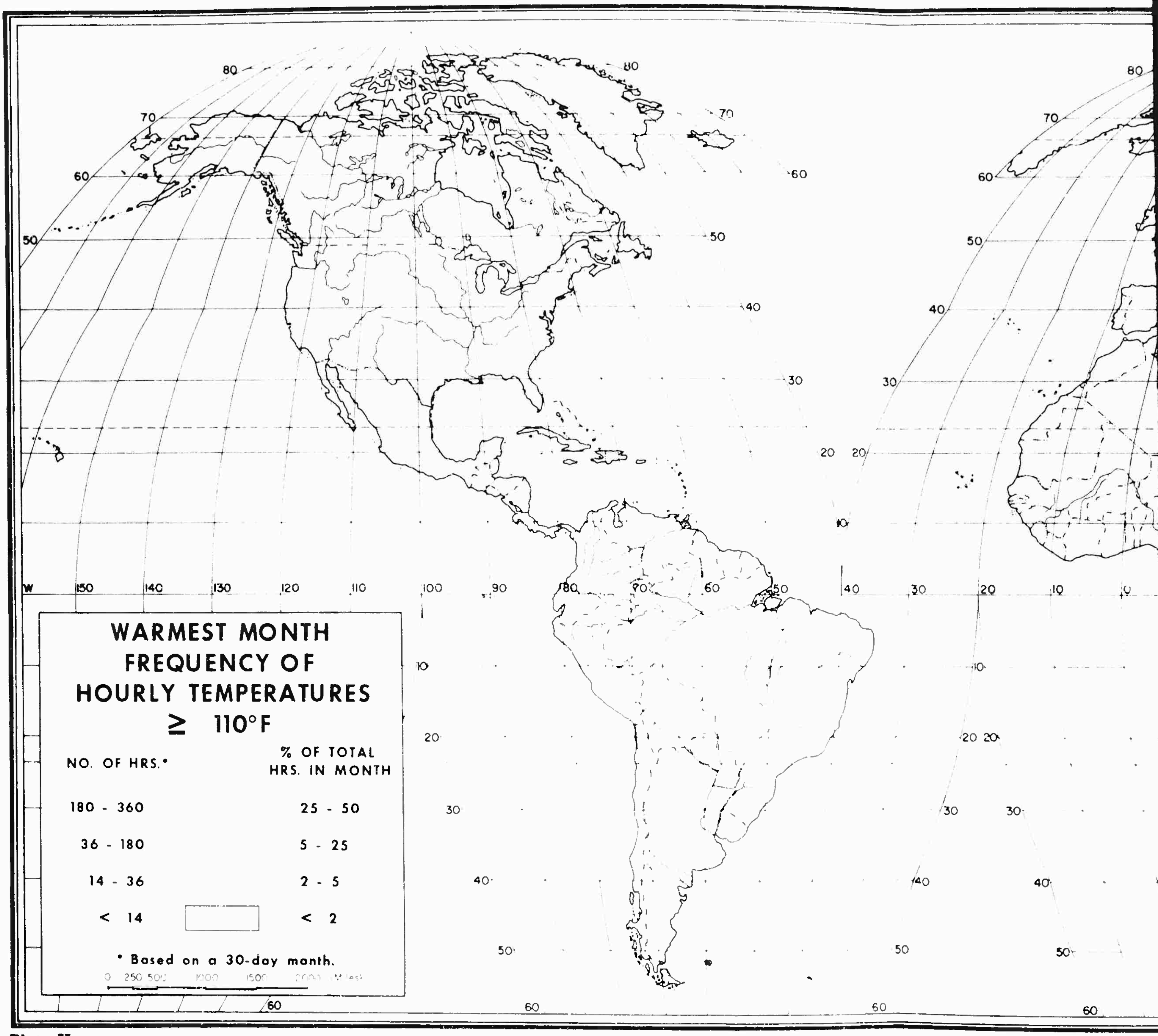
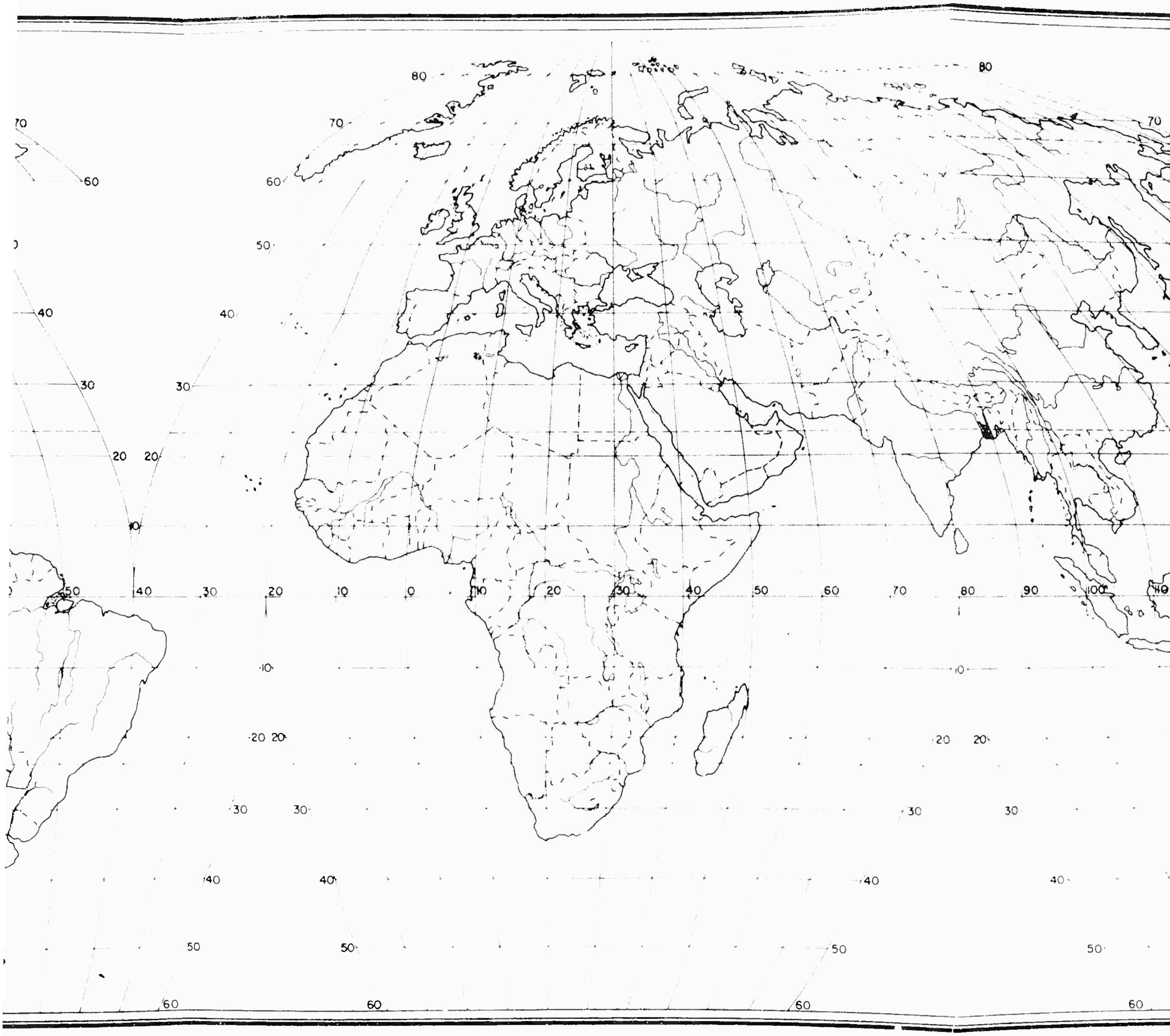
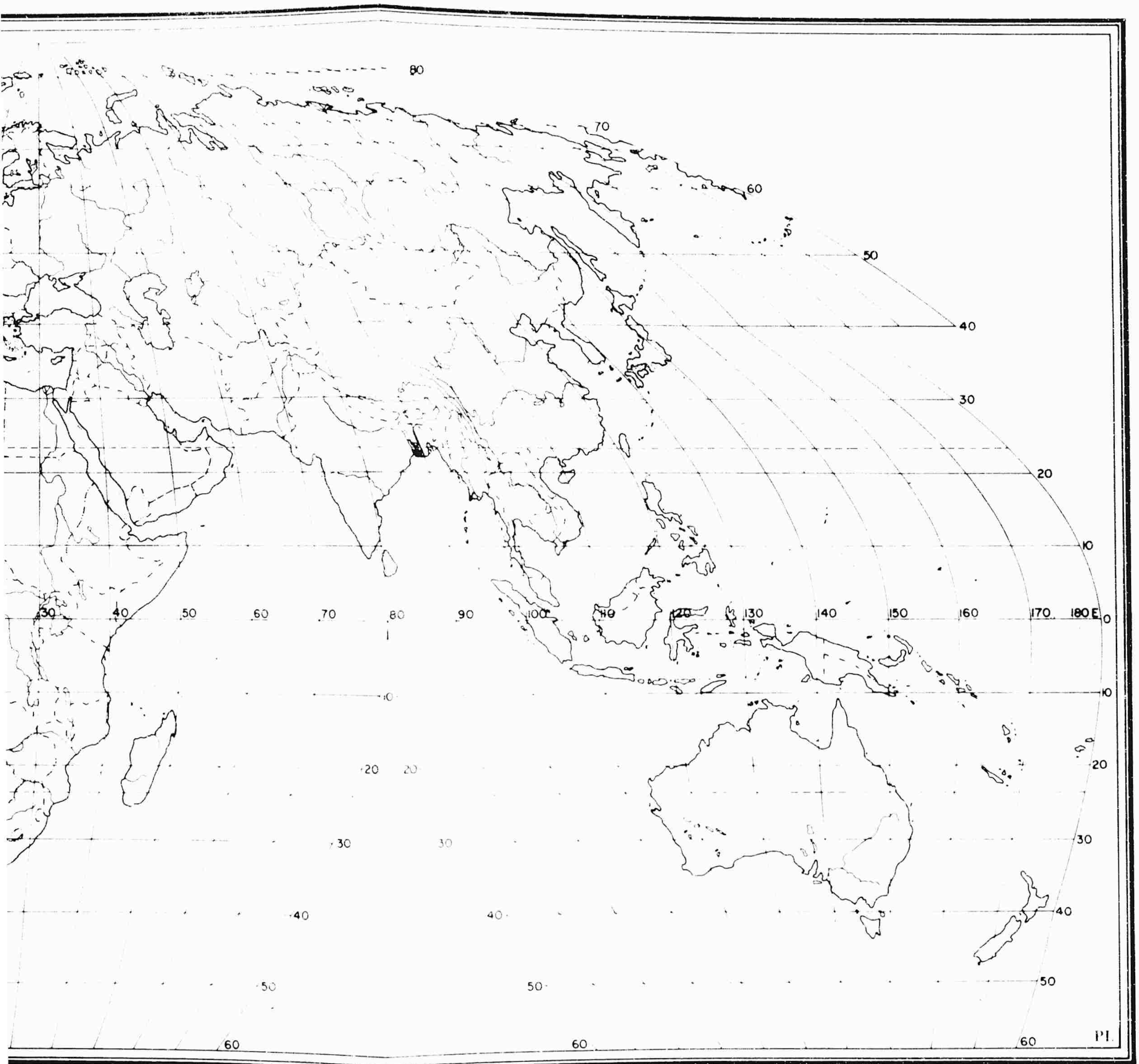

WARMEST MONTH
FREQUENCY OF
HOURLY TEMPERATURES
≥ 110°F
NO. OF HRS.*
% OF TOTAL HRS. IN MONTH
180 - 360
25 - 50
36 - 180
5 - 25
14 - 36
2 - 5
< 14
< 2
* Based on a 30-day month.

Plate X


80
70
60
50
40
30
20
10
50 40 30 20 10 0 10 20 30 40 50 60 70 80 90 100 110
10
20
30
40
50
60

2



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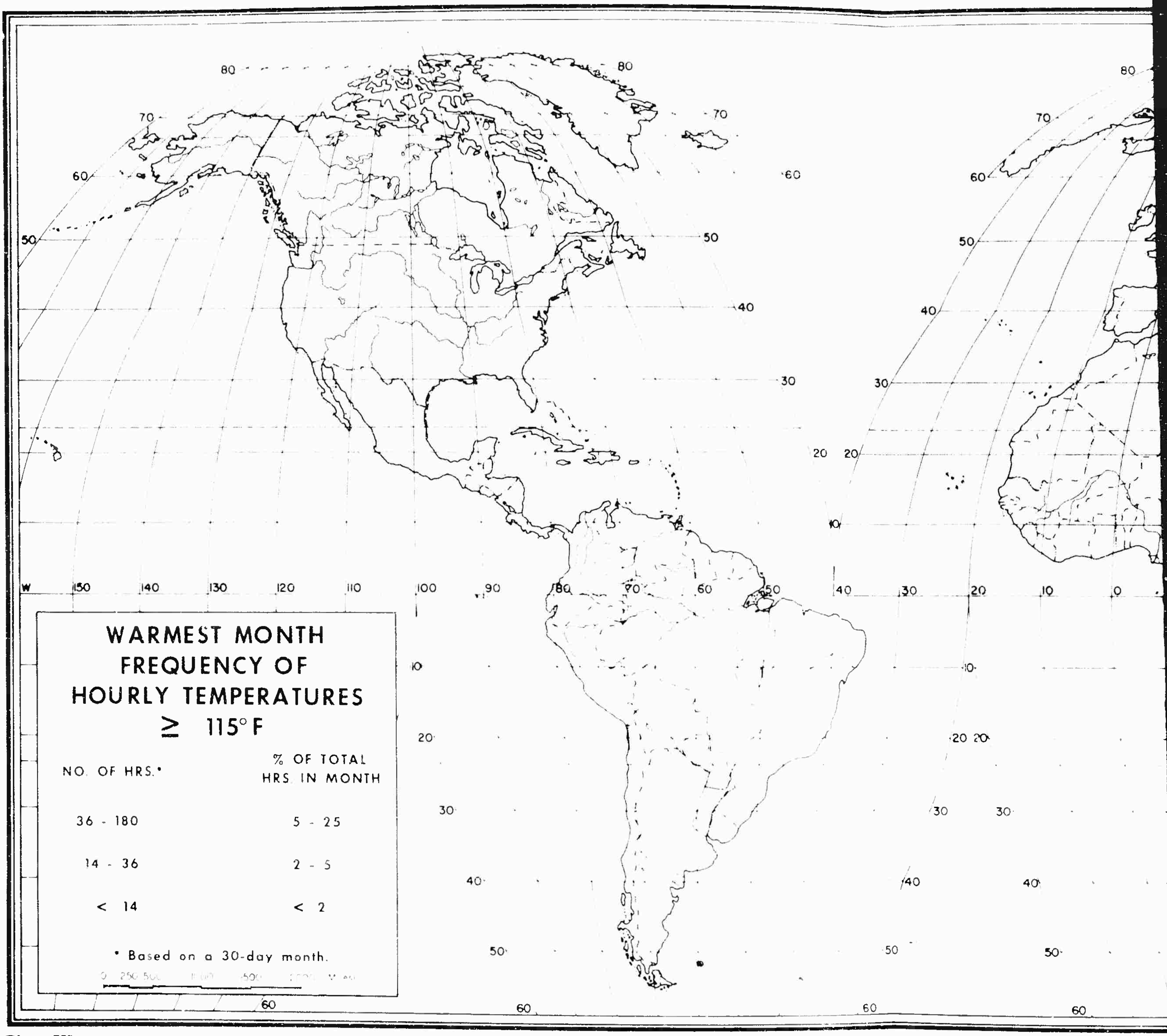
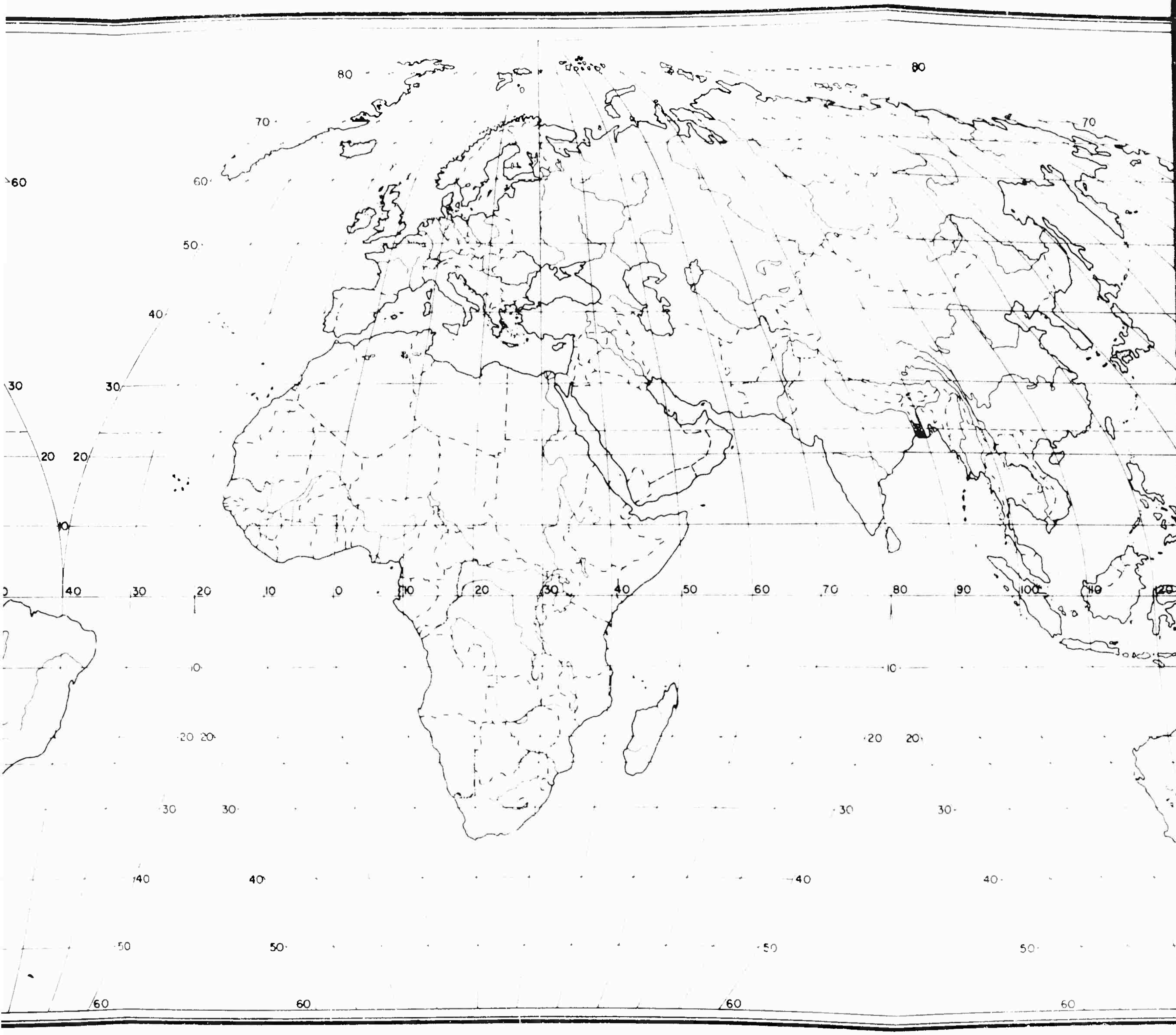
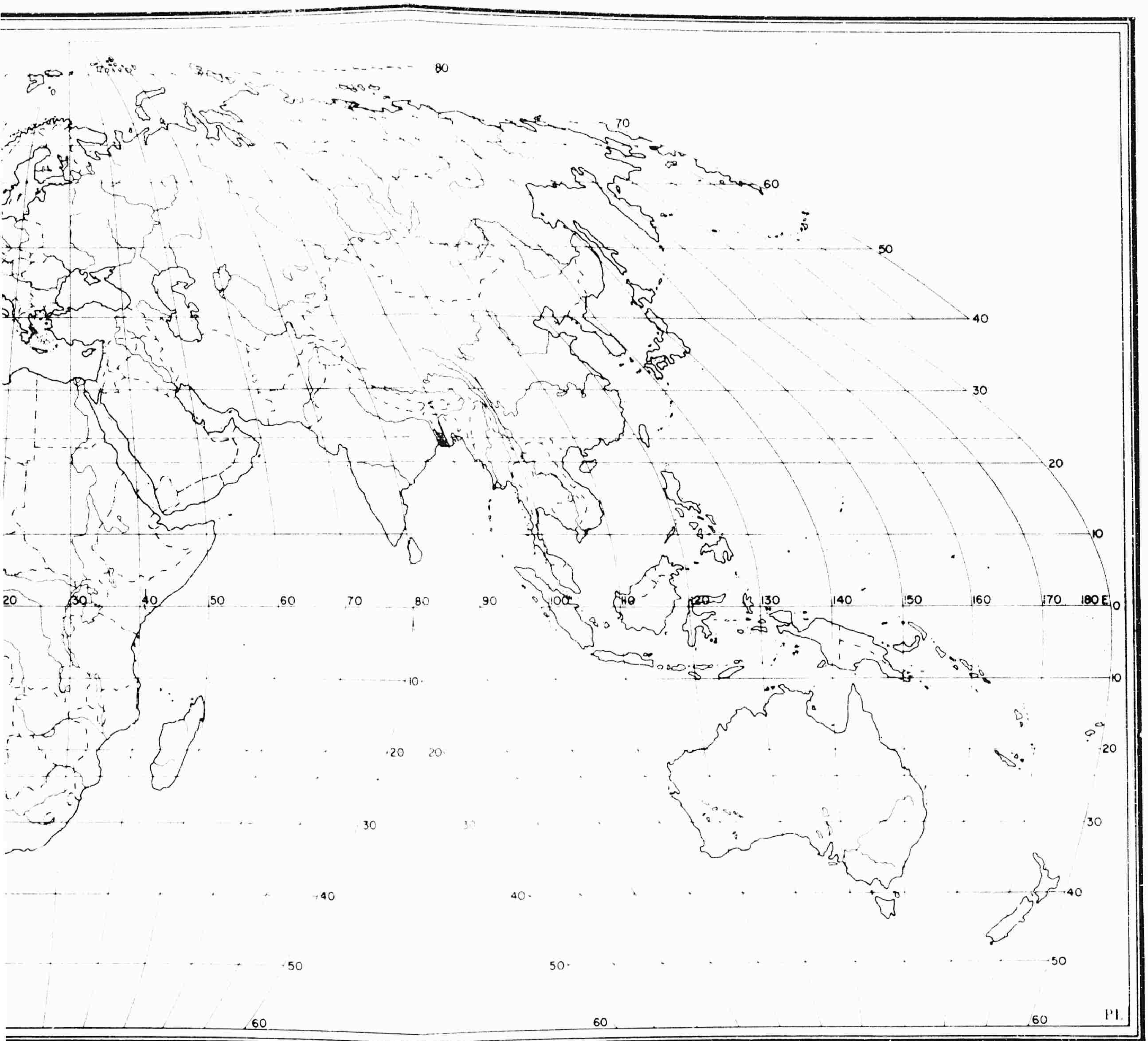

WARMEST MONTH
FREQUENCY OF
HOURLY TEMPERATURES
≥ 115° F
NO. OF HRS.*
% OF TOTAL HRS. IN MONTH
36 - 180
5 - 25
14 - 36
2 - 5
< 14
< 2
* Based on a 30-day month.

Plate XI


80
70
60
50
40
30
20
10
40 30 20 10 0 10 20 30 40 50 60 70 80 90 100 110 120
10
20 20
30 30
40 40
50 50
60 60

2



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3

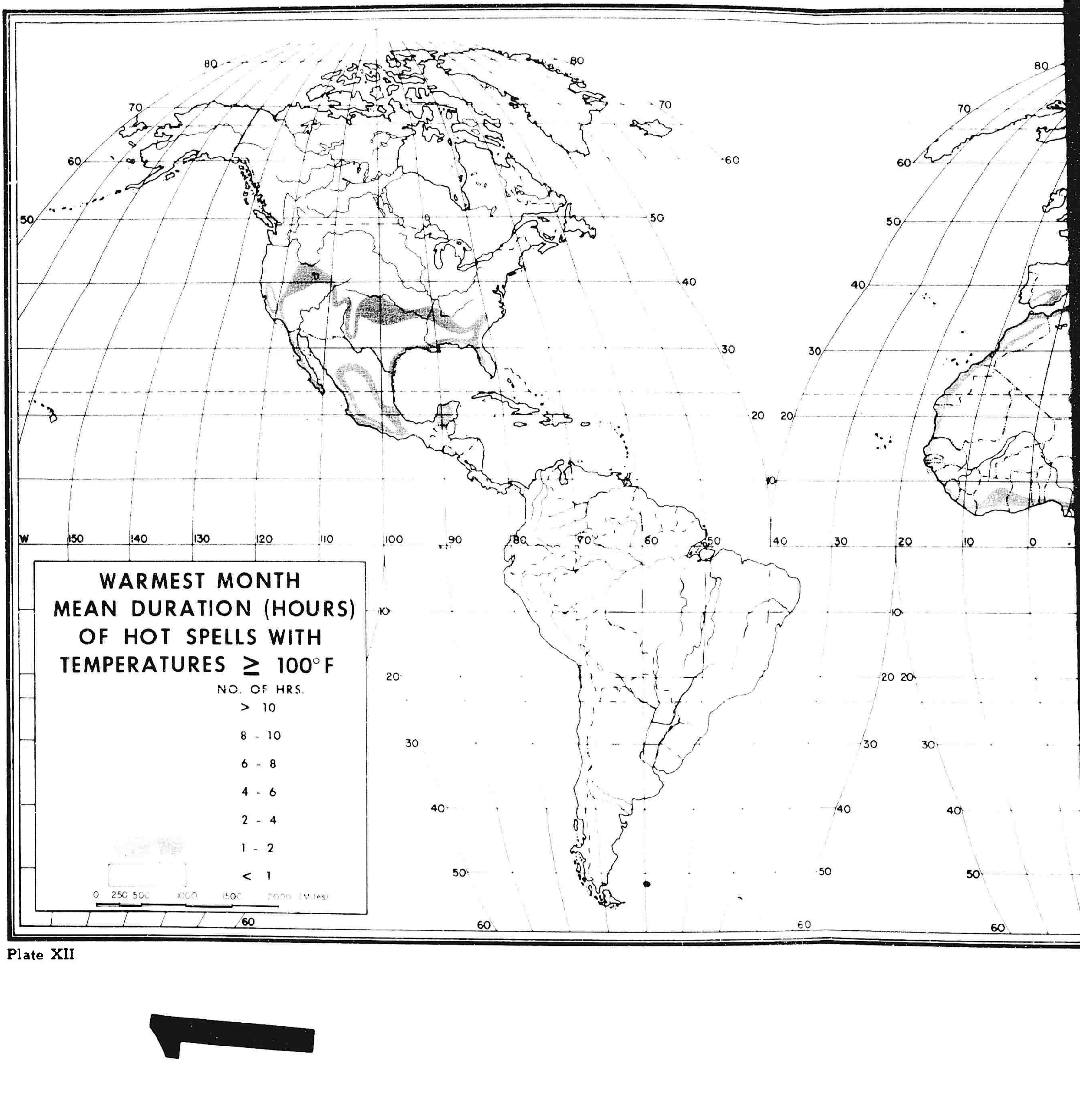
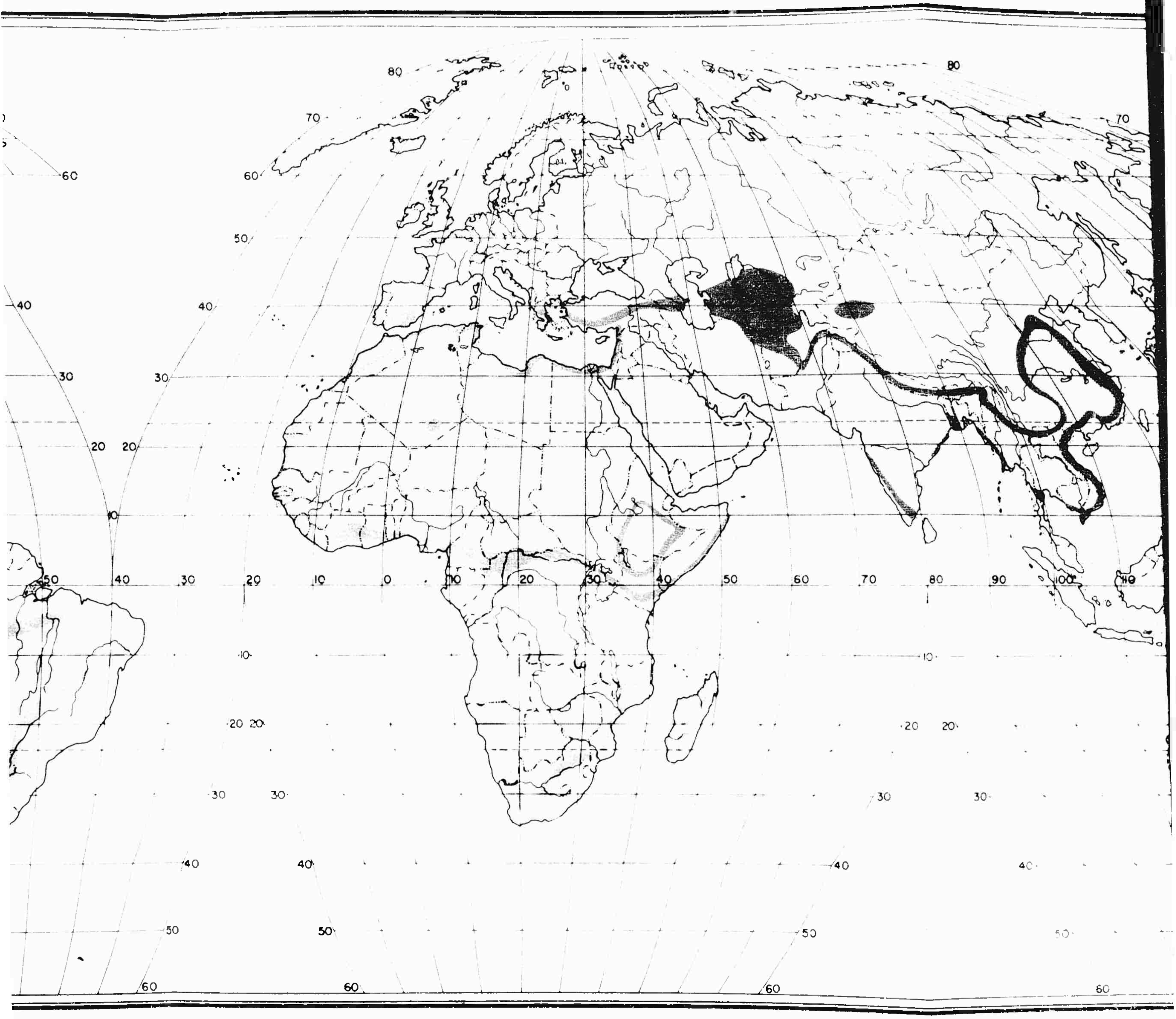

WARMEST MONTH
MEAN DURATION (HOURS)
OF HOT SPELLS WITH
TEMPERATURES ≥ 100° F
NO. OF HRS.
> 10
8 - 10
6 - 8
4 - 6
2 - 4
1 - 2
< 1
0 250 500 1000 1500 2000 (Miles)

Plate XII



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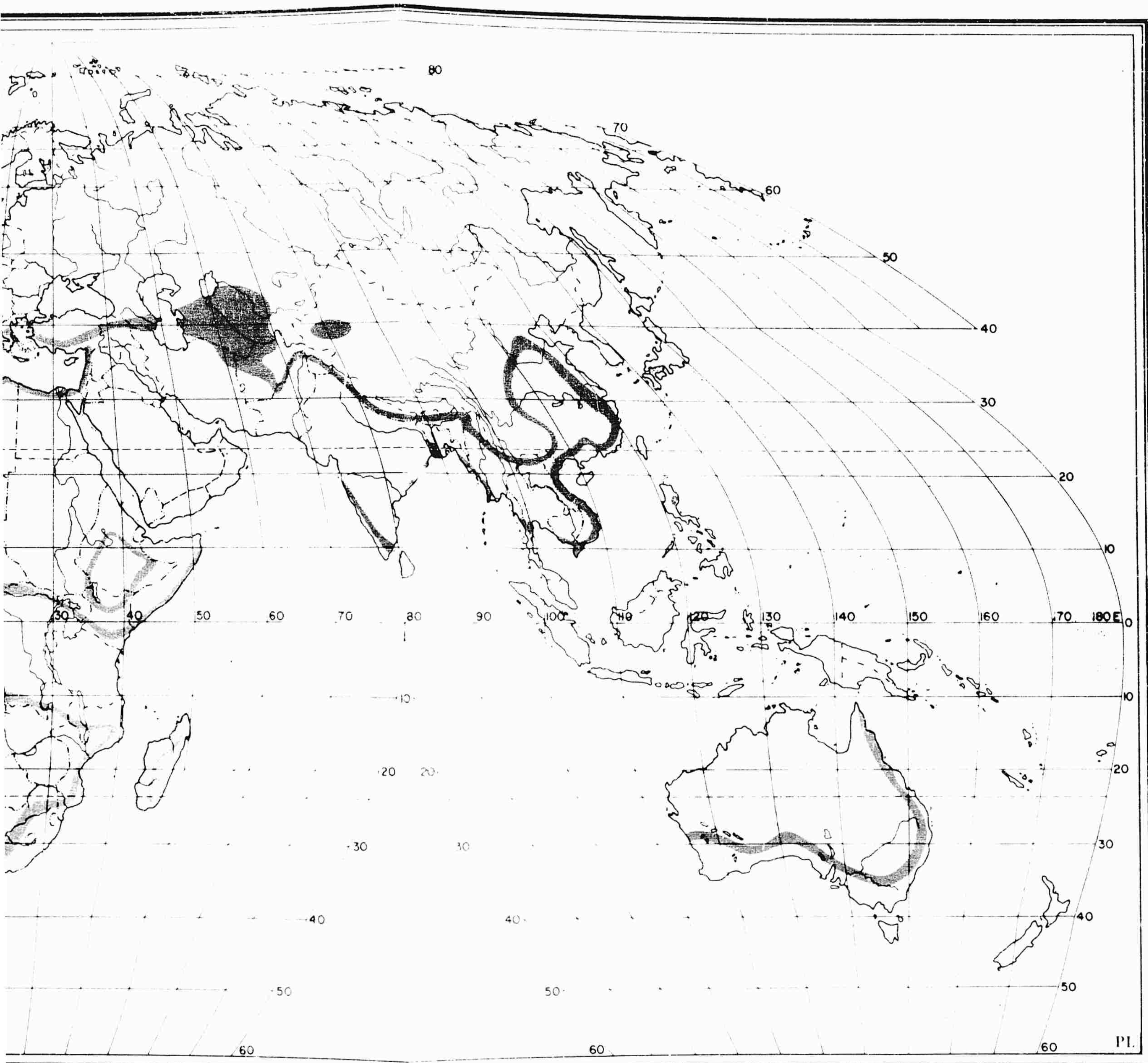

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3

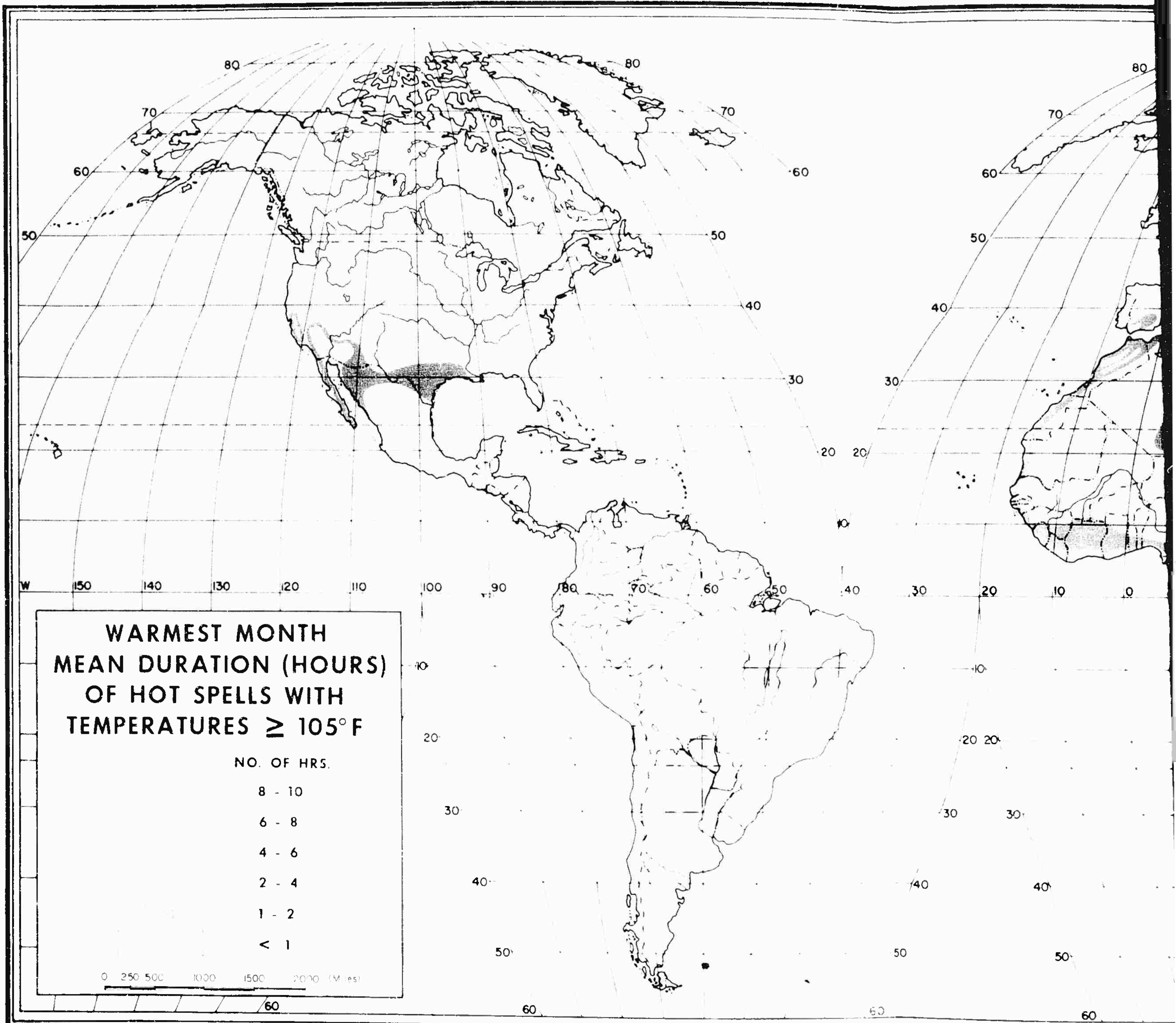
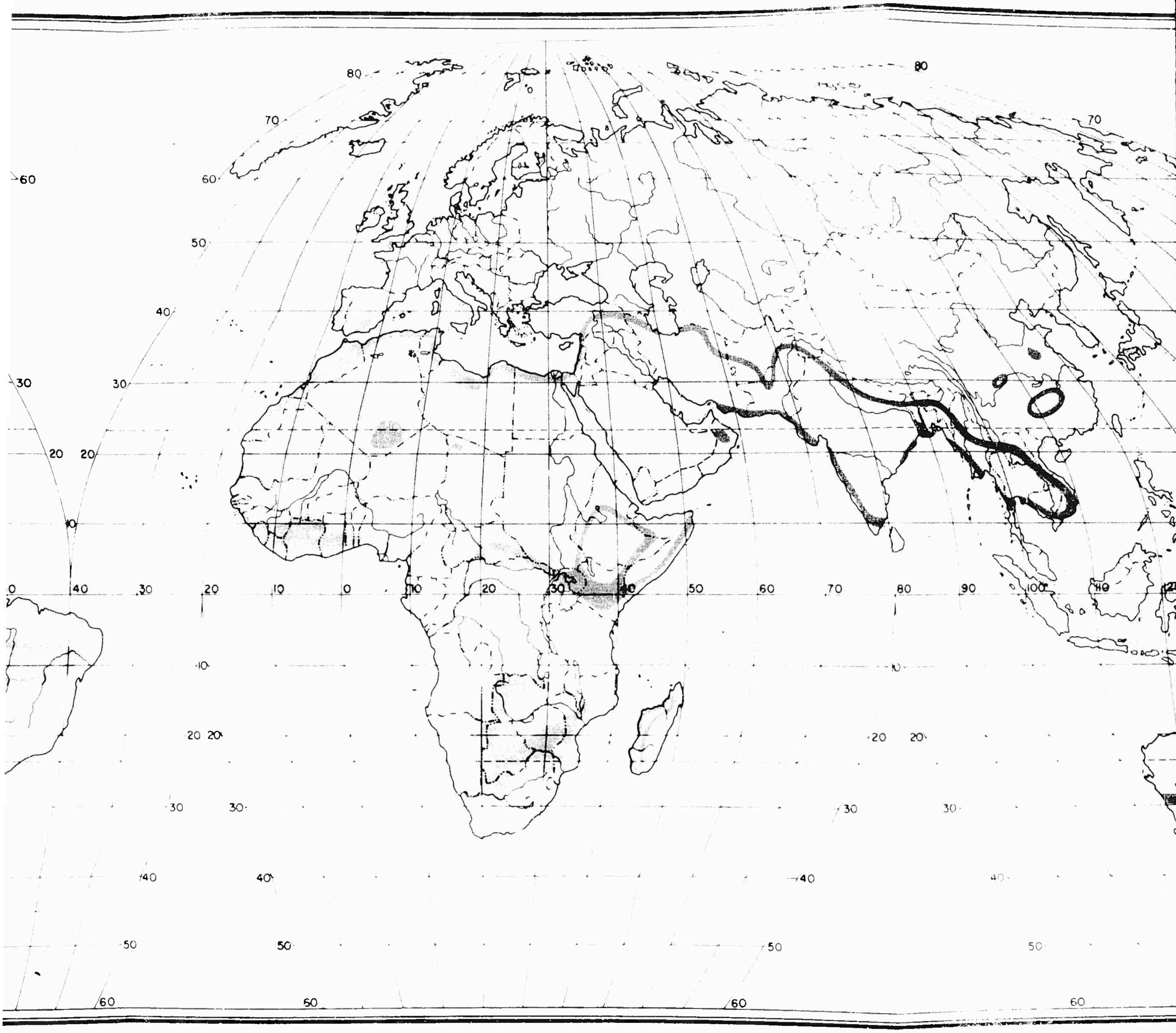

WARMEST MONTH
MEAN DURATION (HOURS)
OF HOT SPELLS WITH
TEMPERATURES ≥ 105°F
NO. OF HRS.
8 - 10
6 - 8
4 - 6
2 - 4
1 - 2
< 1
0 250 500 1000 1500 2000 (Miles)

Plate XIII



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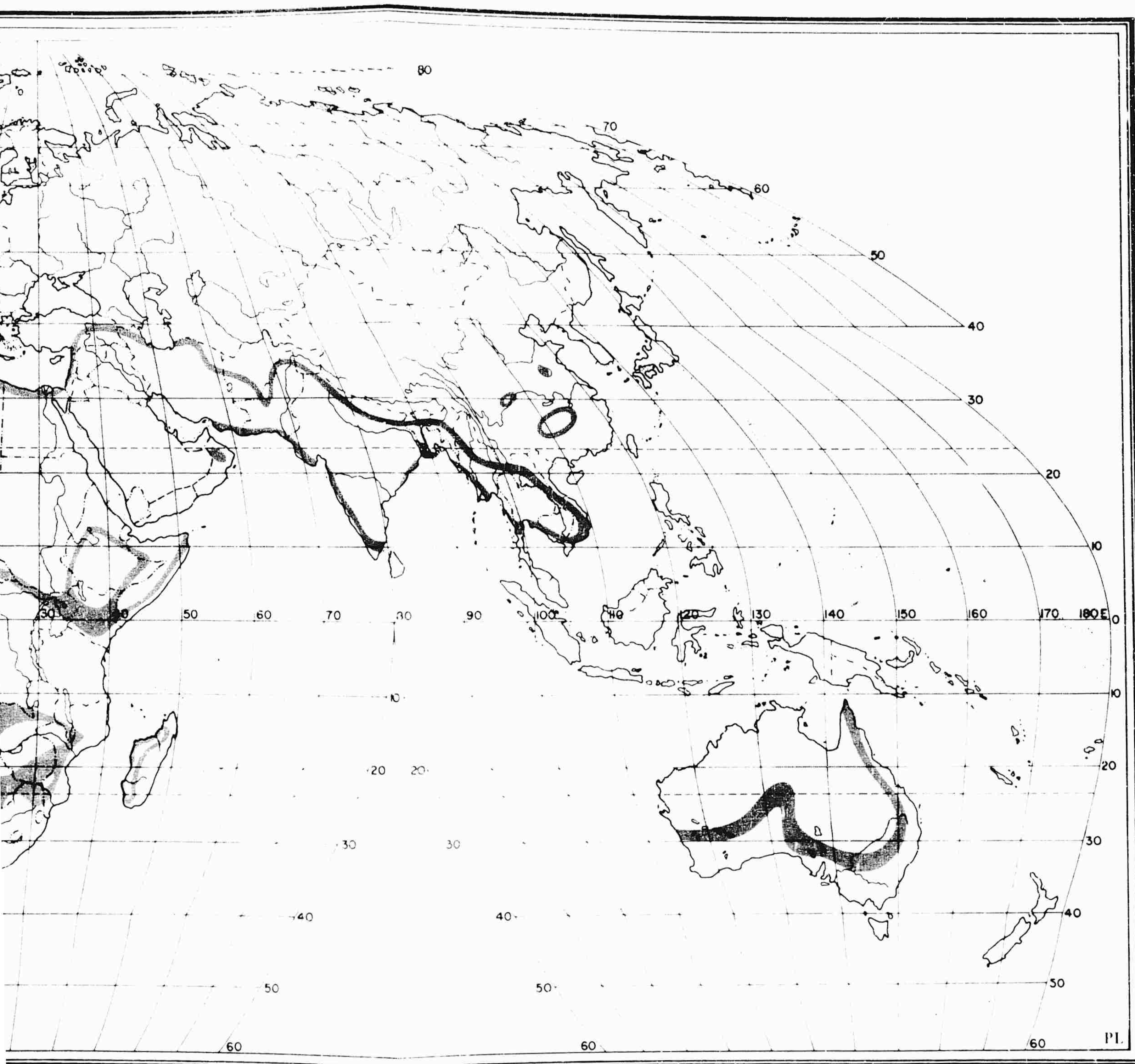

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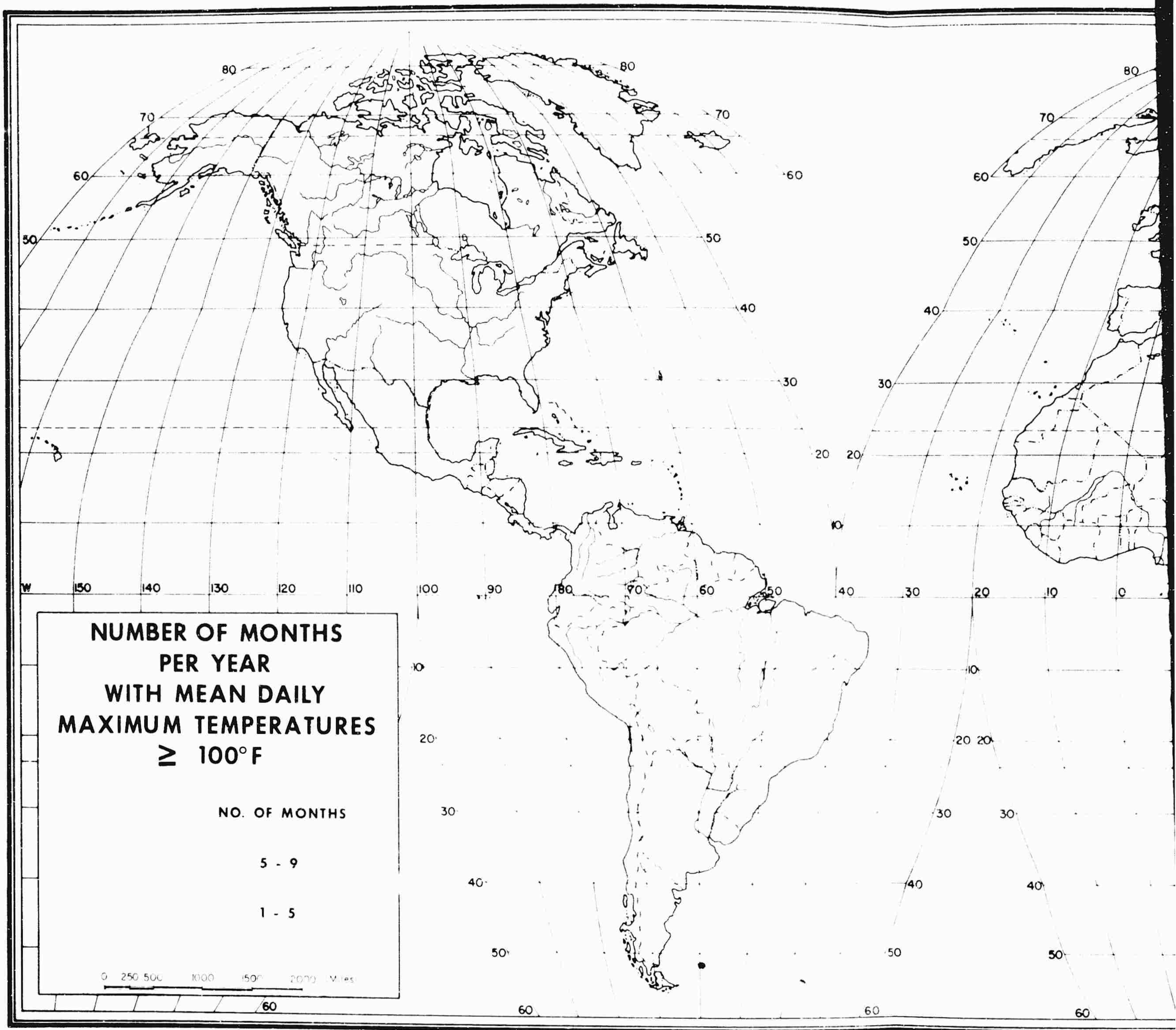
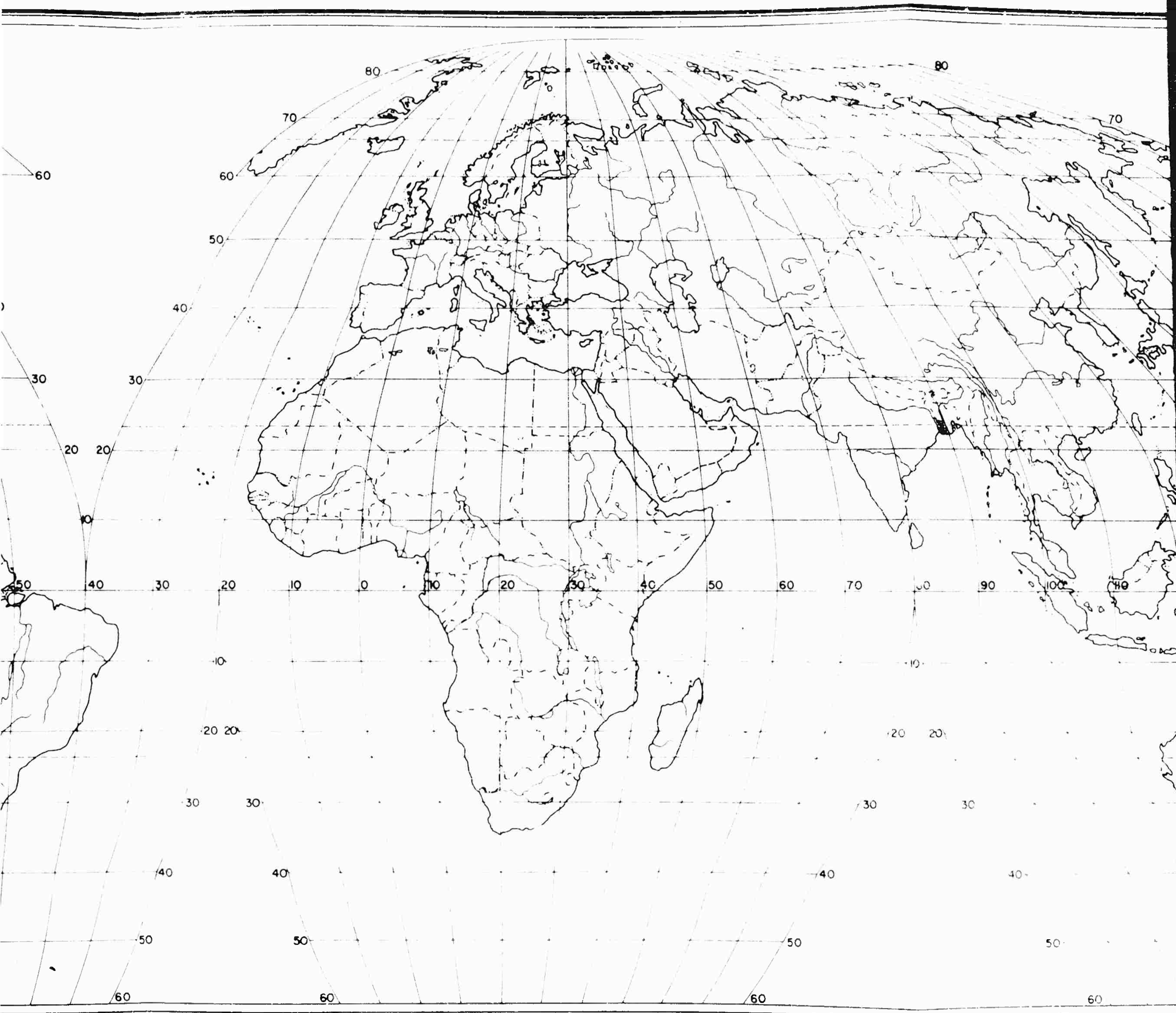

NUMBER OF MONTHS
PER YEAR
WITH MEAN DAILY
MAXIMUM TEMPERATURES
≥ 100°F
NO. OF MONTHS
5 - 9
1 - 5
0 250 500 1000 1500 2000 Miles

Plate XIV



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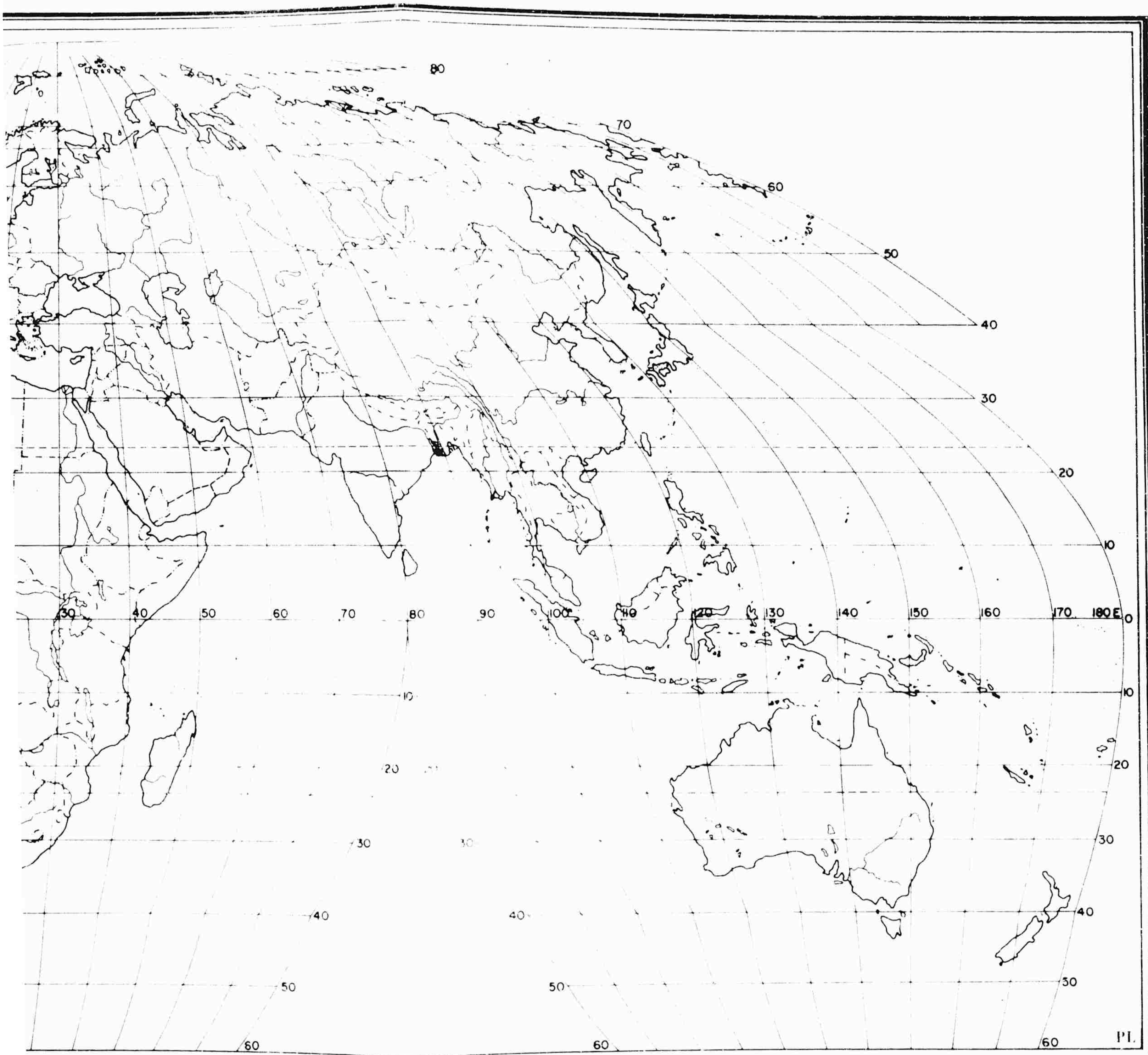

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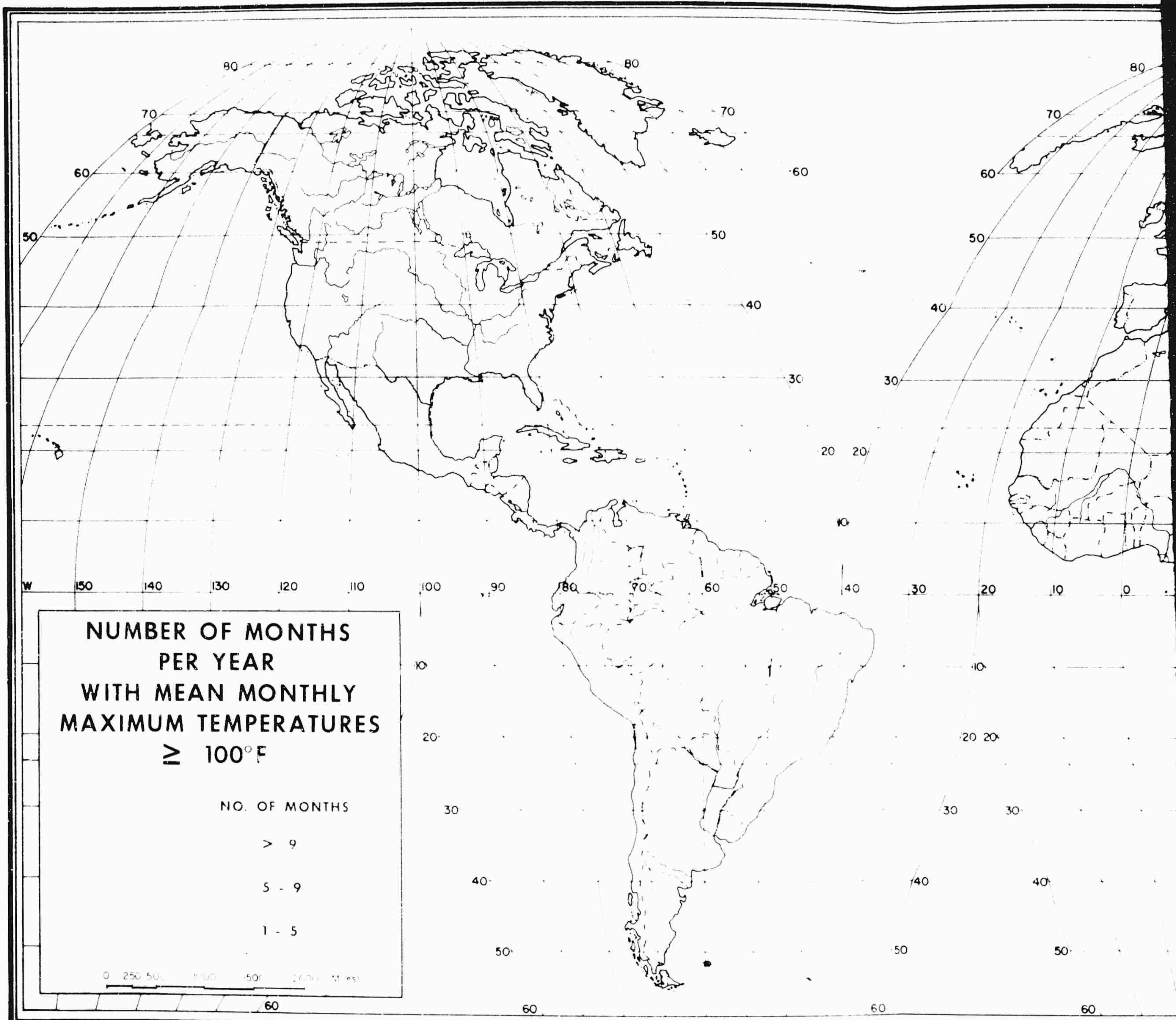
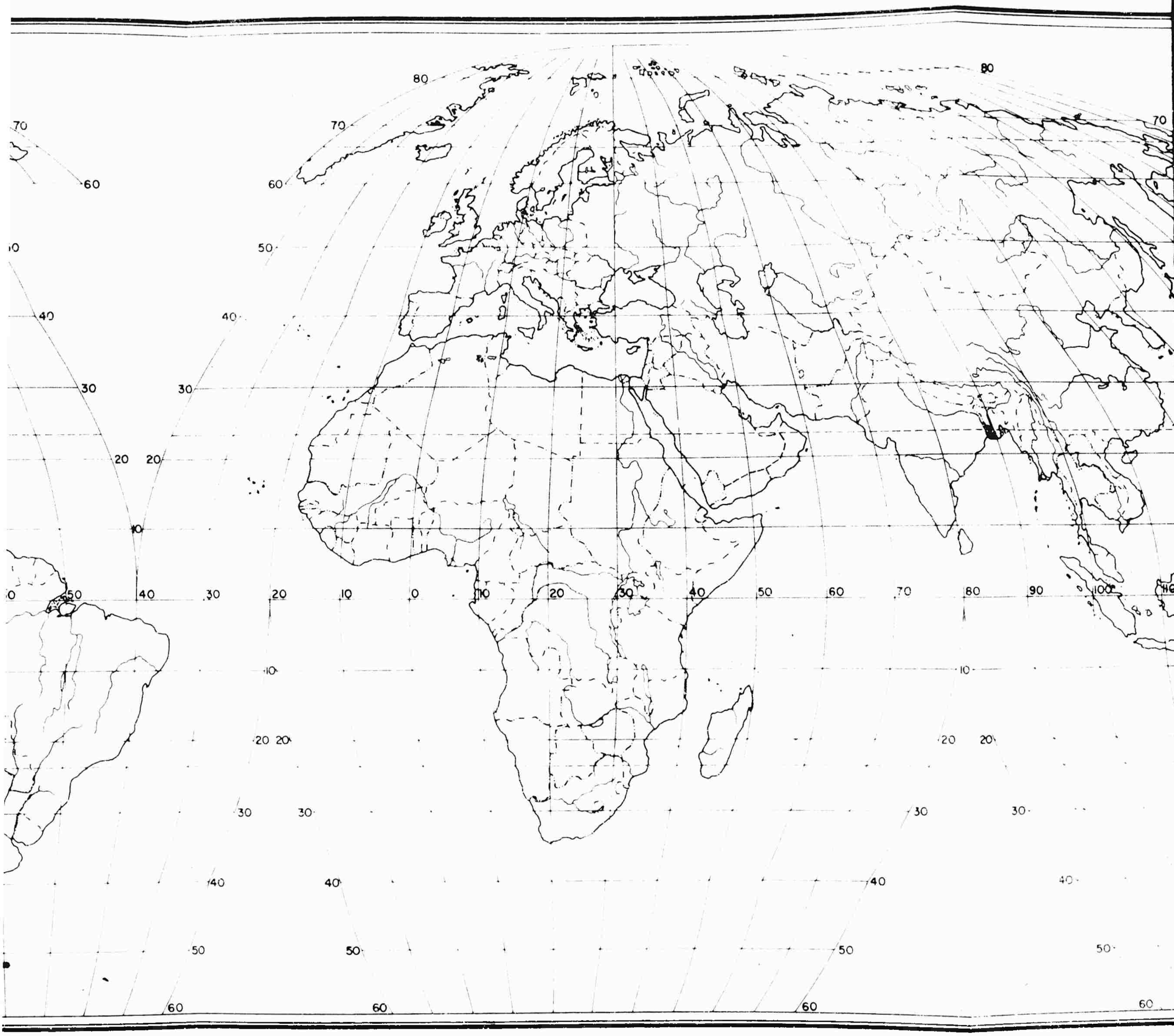

NUMBER OF MONTHS
PER YEAR
WITH MEAN MONTHLY
MAXIMUM TEMPERATURES
≥ 100°F
NO. OF MONTHS
> 9
5 - 9
1 - 5

Plate XV



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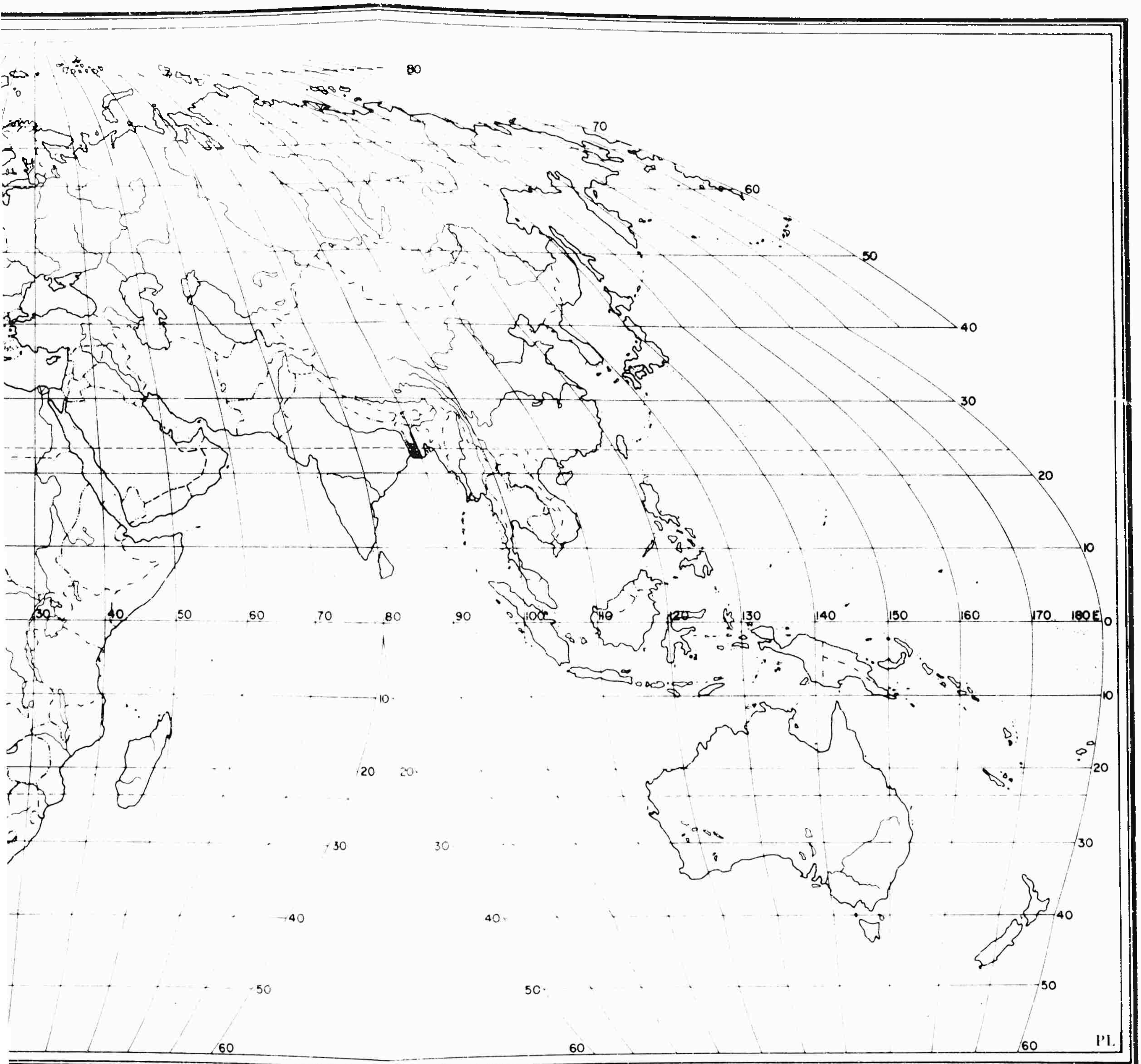

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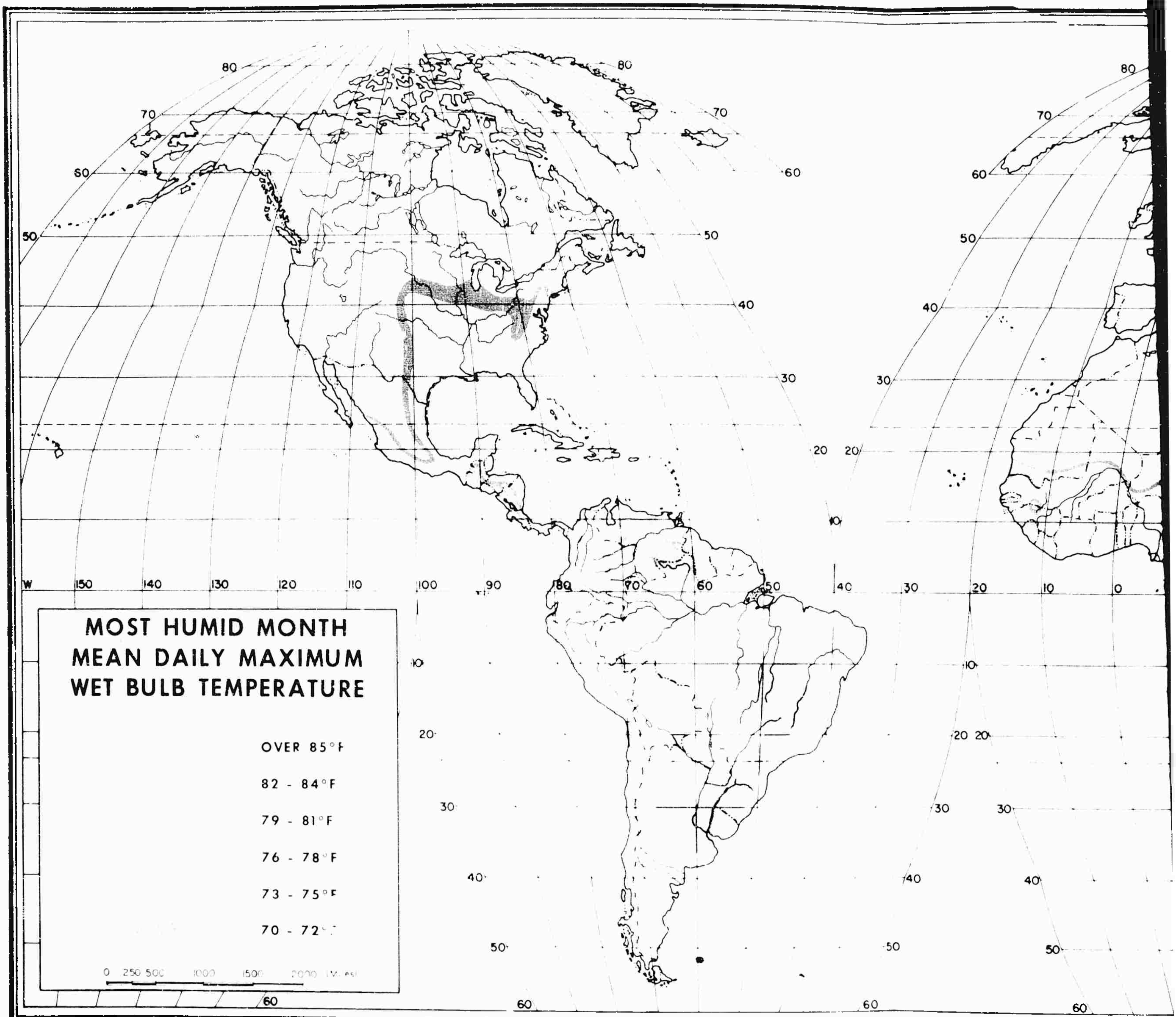
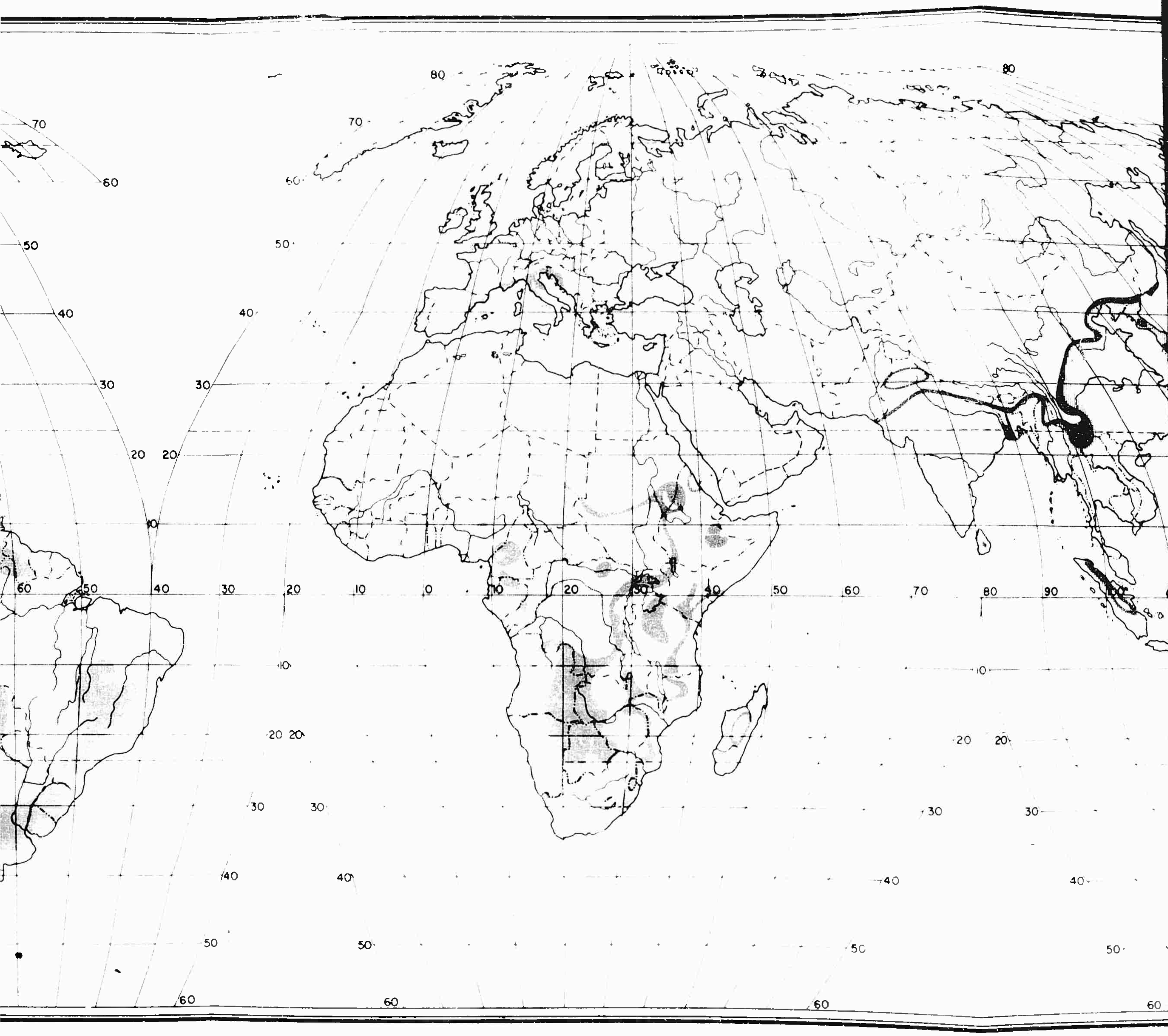

MOST HUMID MONTH
MEAN DAILY MAXIMUM
WET BULB TEMPERATURE
OVER 85°F
82 - 84°F
79 - 81°F
76 - 78°F
73 - 75°F
70 - 72
0 250 500 1000 1500

Plate XVI



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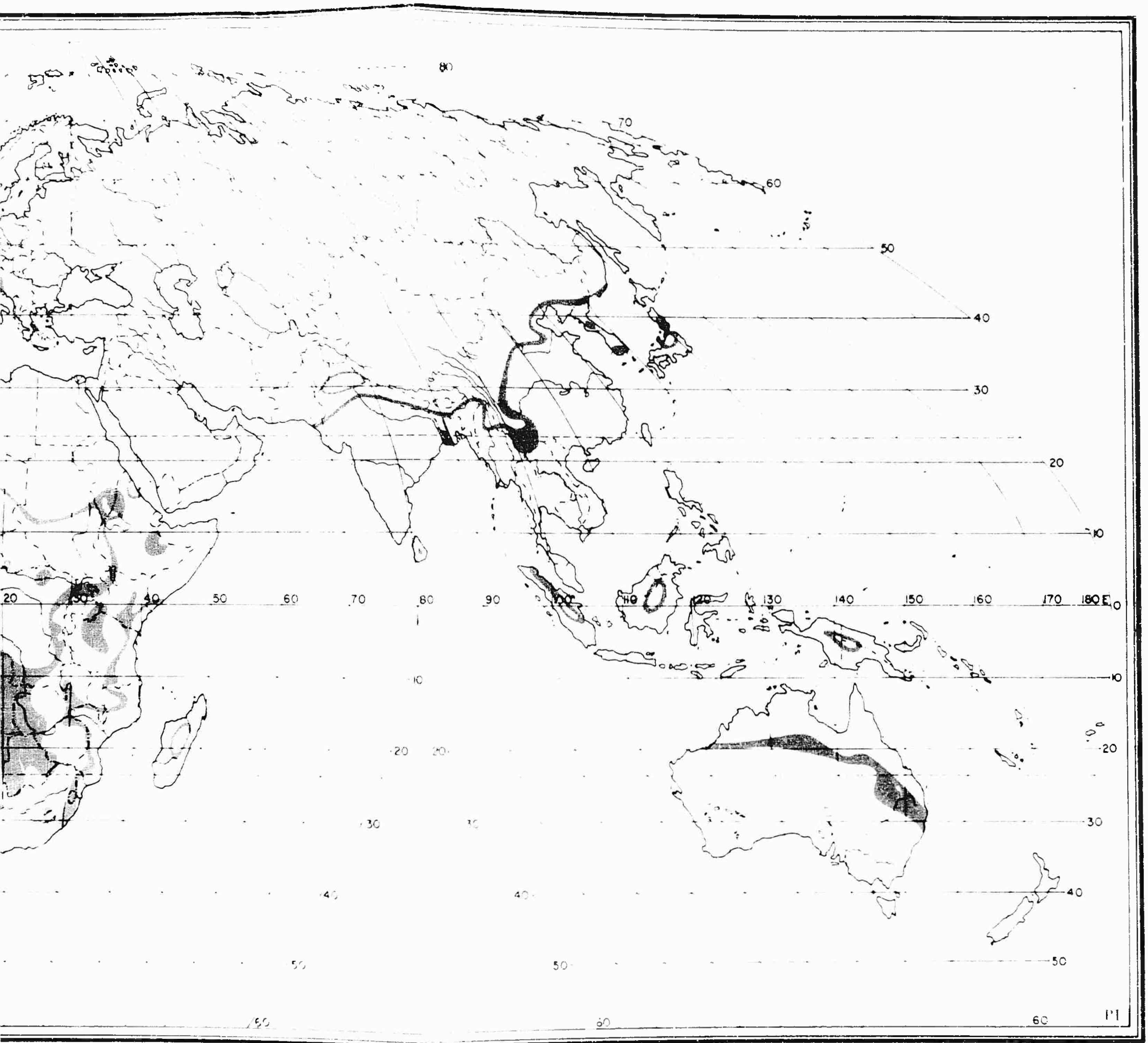

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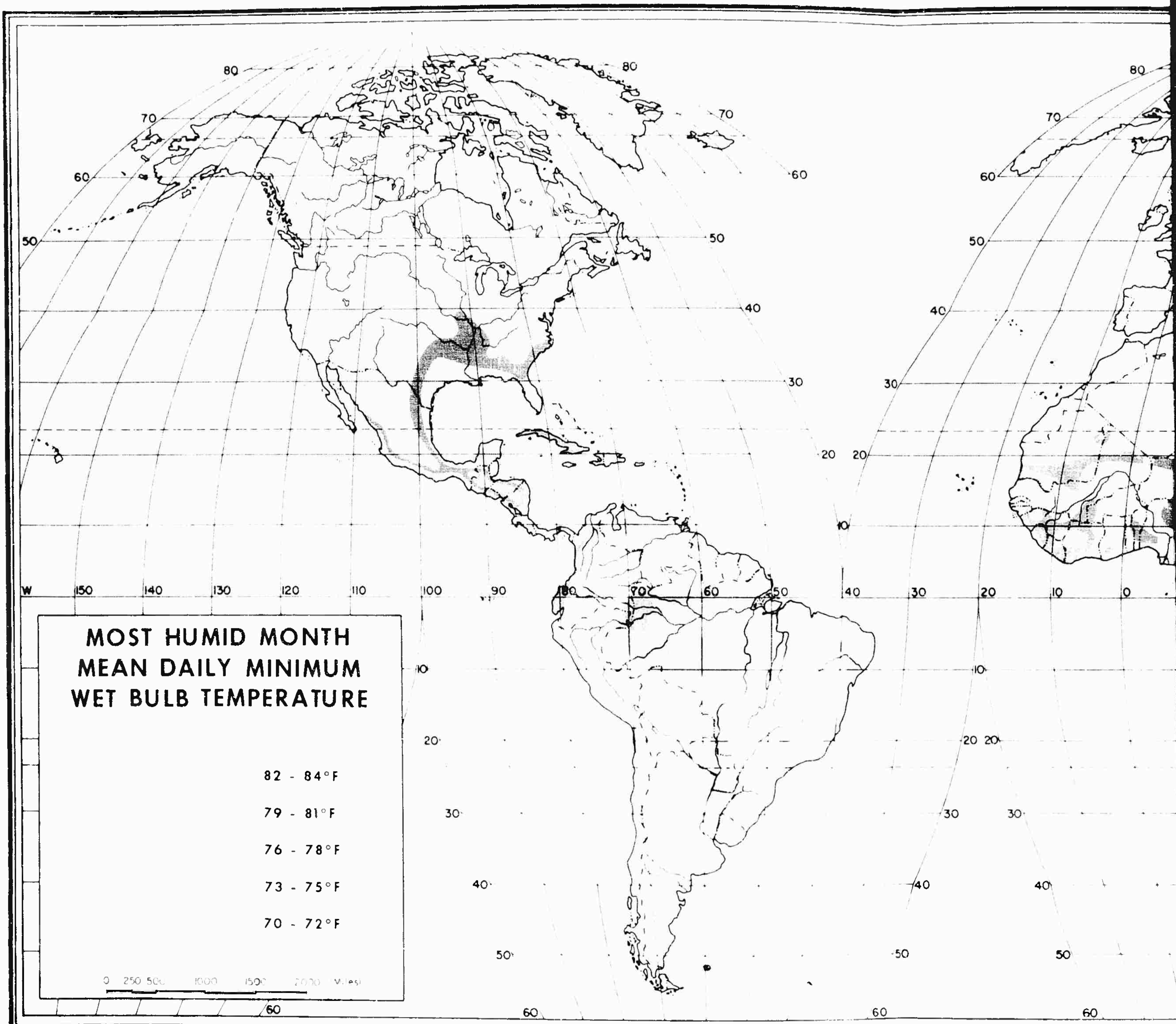
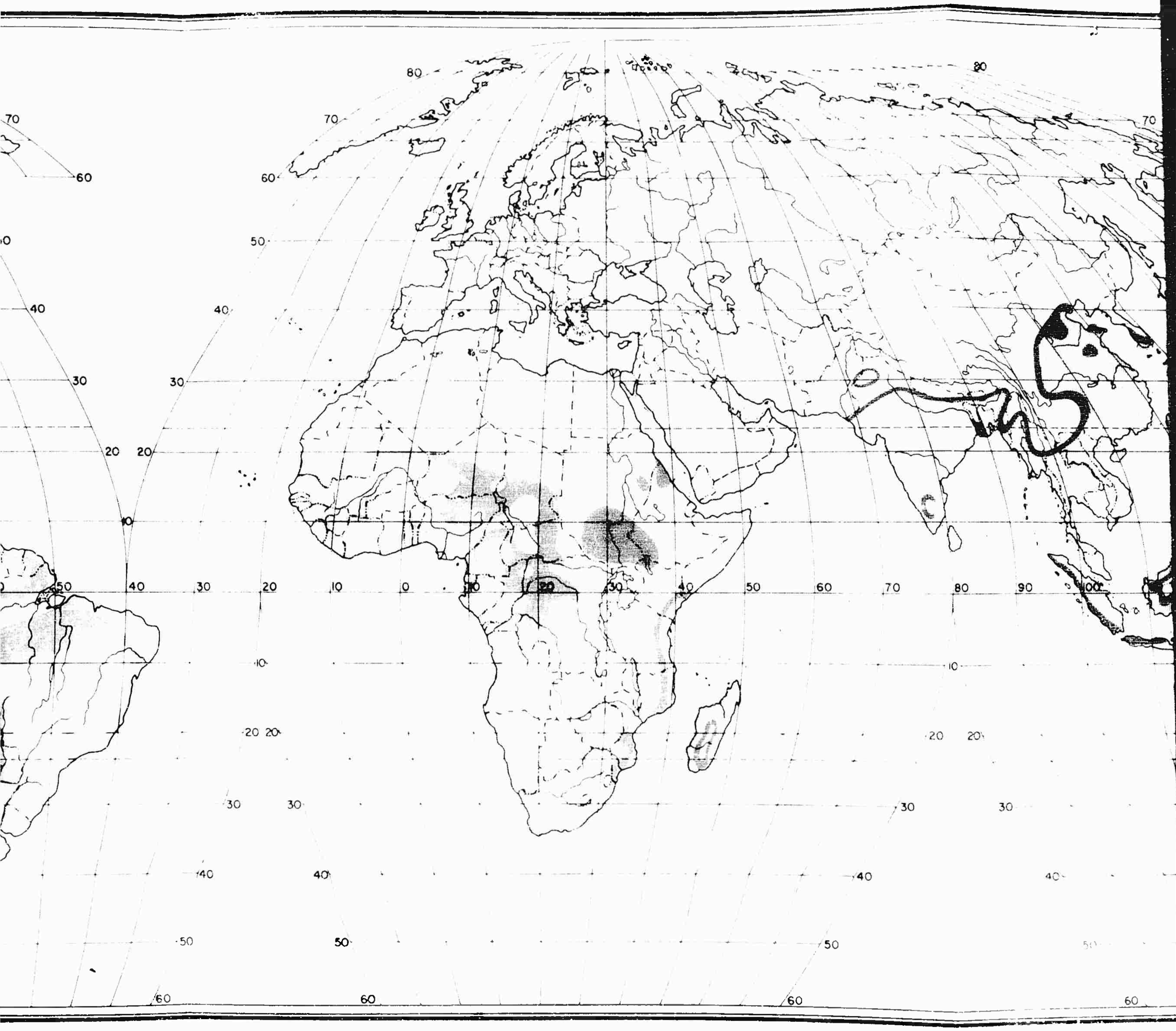


MOST HUMID MONTH
MEAN DAILY MINIMUM
WET BULB TEMPERATURE
82 - 84°F
79 - 81°F
76 - 78°F
73 - 75°F
70 - 72°F

Plate XVII



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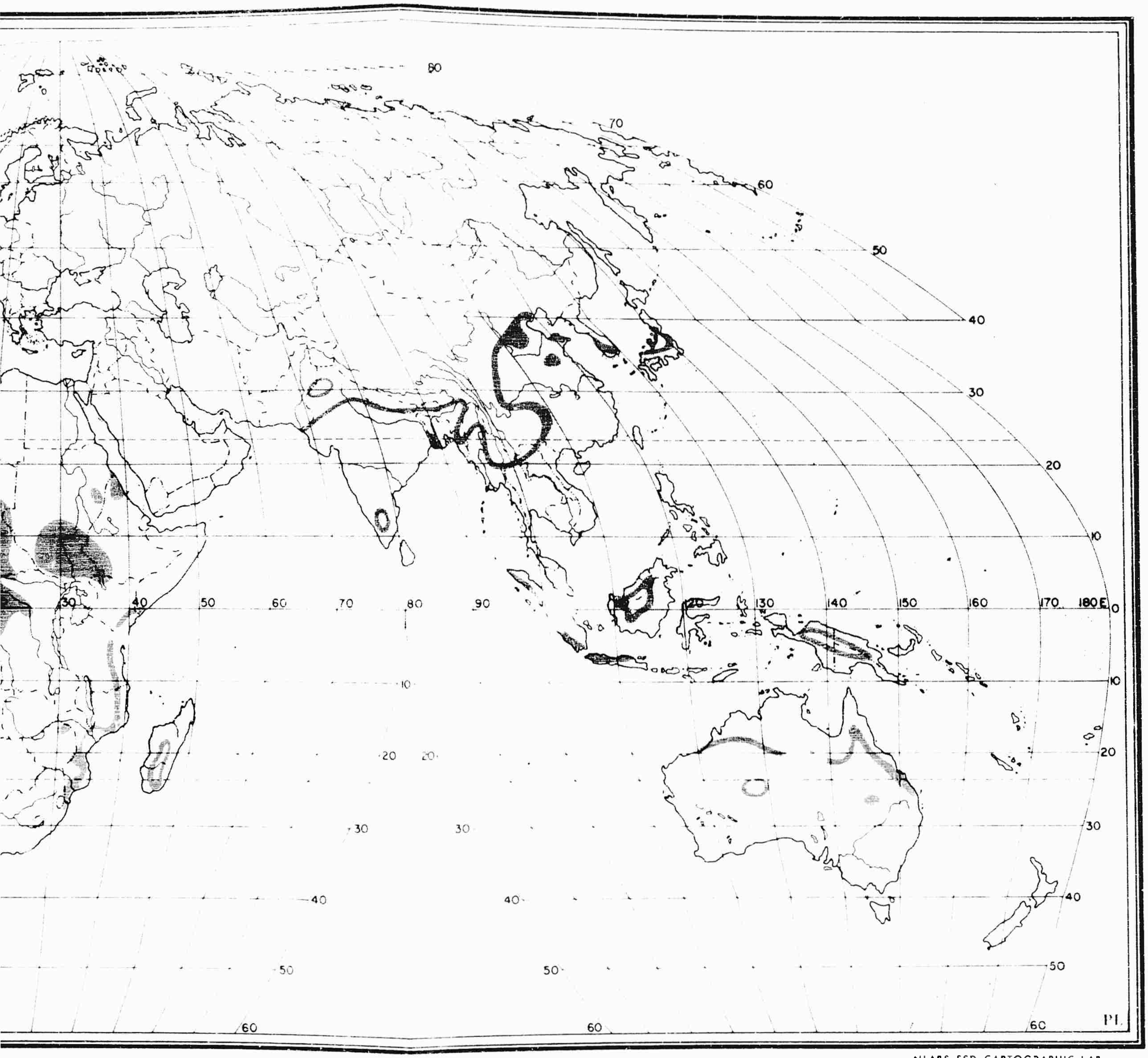

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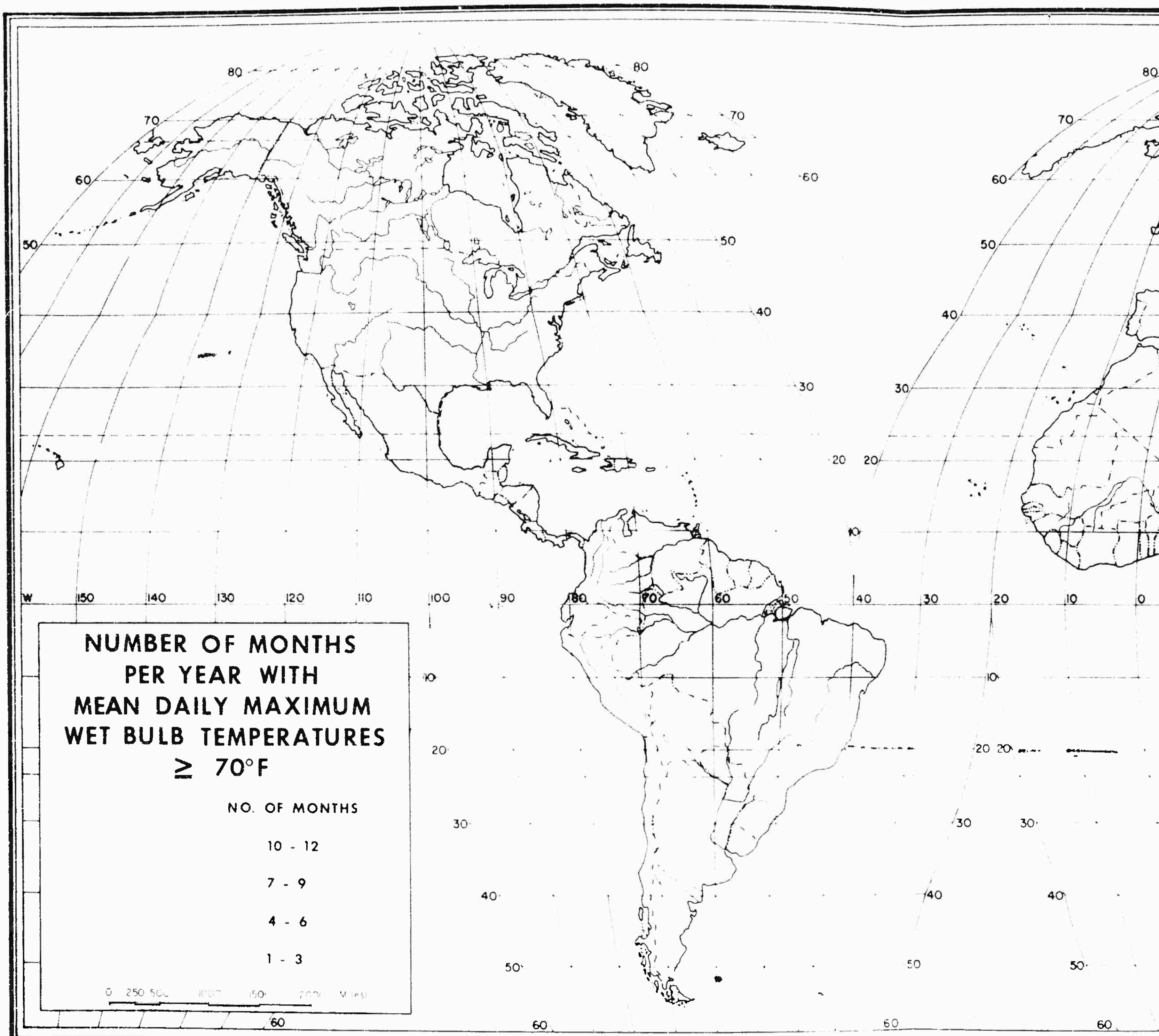
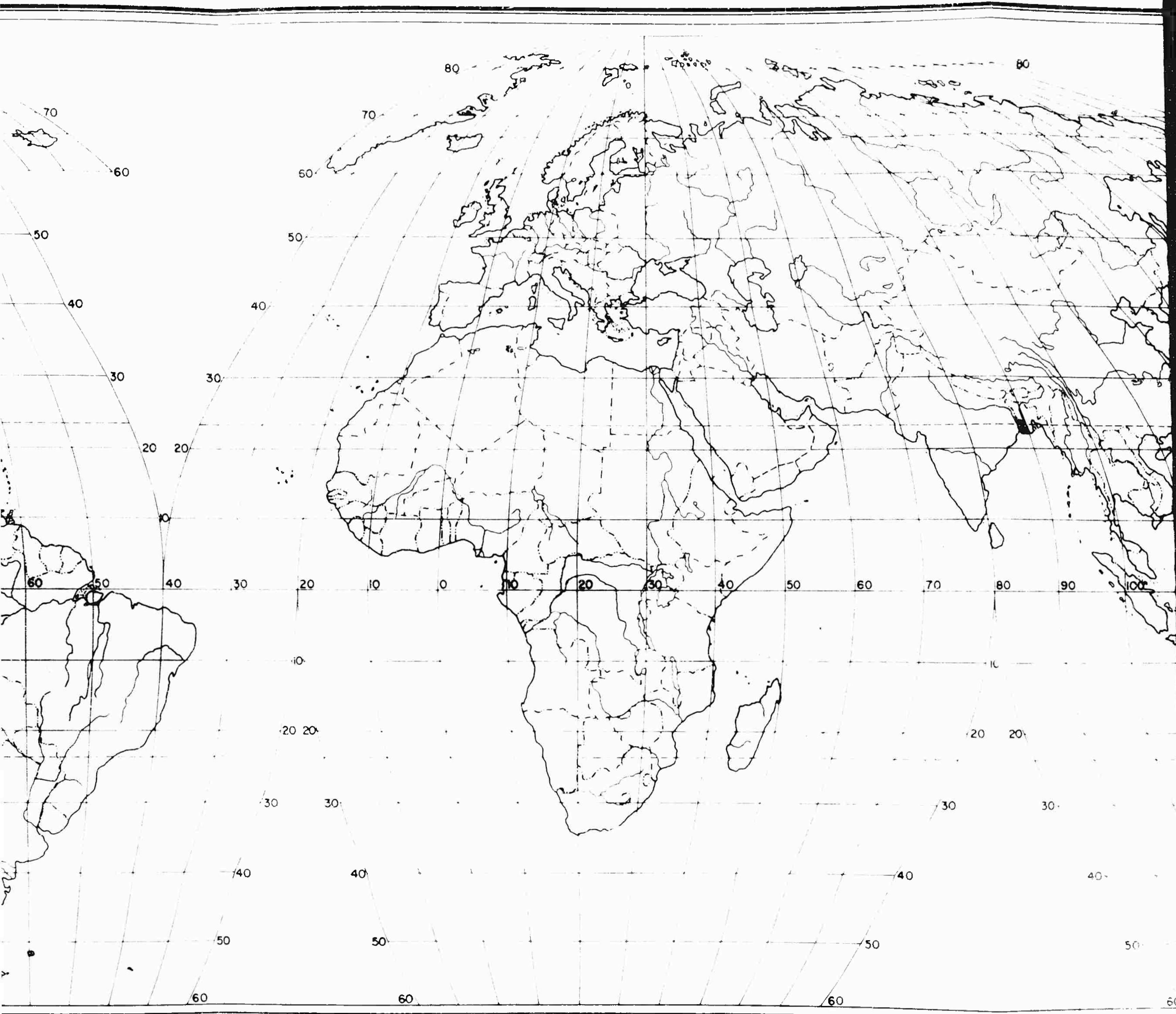

NUMBER OF MONTHS
PER YEAR WITH
MEAN DAILY MAXIMUM
WET BULB TEMPERATURES
≥ 70°F
NO. OF MONTHS
10 - 12
7 - 9
4 - 6
1 - 3

Plate XVIII



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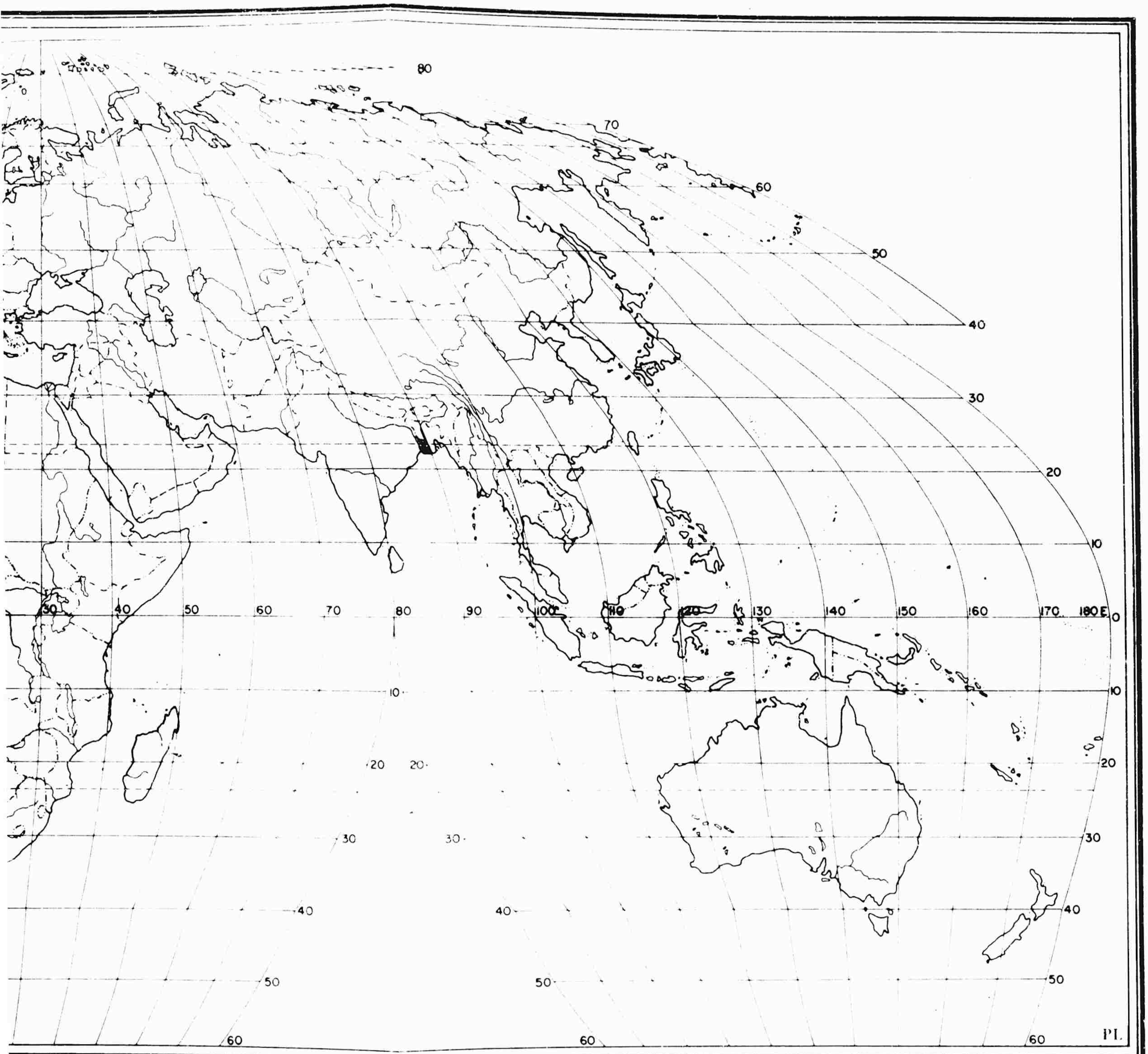

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